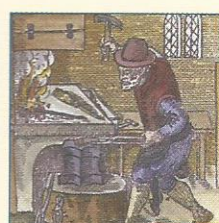
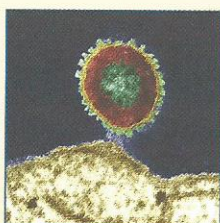
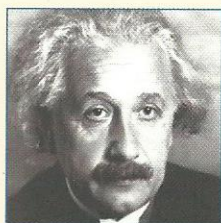


The Oxford

ILLUSTRATED COMPANION TO THE HISTORY OF MODERN SCIENCE



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246, 278, 287, 289, 296/Michael Abbey, 80/National Library of Medicine: 10, 151, 200, 206/NCAR, 62/New York Public Library,
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272, 291, 292, 298, 299, 310/Science Source: 40, 82, 89, 92, 124, 150, 162, 164, 165, 174, 185, 195, 202, 214, 222, 270, 278, 306/
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Published by Tess Press, an imprint of
Black Dog & Leventhal Publishers, Inc.
151 West 19th Street
New York, NY 10011

Jacket Design by Lindsay Wolff
Interior Design by Red Herring Design

ISBN: 978-1-60376-036-2

Printed in China

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ACADEMIES AND LEARNED SOCIETIES. “Ci-gît un qui ne fut rien, pas même académicien” (“Here lies someone who was nobody, not even an academician”). This epitaph, on a tombstone now in the Musée des Beaux Arts in Dijon, suggests the scale and tone of the academic movement during the Enlightenment. Between 1750 and 1774, seventeen learned societies dedicated at least partly to natural science were founded in France alone. But as the epitaph insinuates, most of the academies of the great age of academies had more to do with society than with science. They drew their memberships primarily from the professions—lawyers, doctors, clerics, and military men—and from landed gentry. They discussed local improvements, maintained a library and collection of instruments, and performed, usually irregularly, the two essential offices of a learned society in the age of Enlightenment: giving prizes to winners of essay competitions and publishing papers presented by its members.

Although the various groups, clubs, and societies that occupied themselves with natural knowledge during the modern period elude exact classification, an academy may be defined sufficiently as a formal institution (however meager its statutes) with a restricted membership (never more than a few hundred before the twentieth century) devoted in substantial part to the advancement of all the natural sciences, particularly by the mutual encouragement of its members. A

university, professional society, research council, museum, laboratory, or observatory is not an academy, although all of them exercise one or more of the same functions—publishing memoirs, encouraging research, funding expeditions, giving prizes, imposing standards, establishing solidarity, and promoting science among the wider society—first brought together in academies.

The earliest scientific academies of any importance appeared in Italy in the seventeenth century as variants of a common Renaissance type—a group of literary men maintained for a few years by a wealthy aristocrat or prelate. The Accademia dei Lincei (1603–1630), organized but not underwritten by a duke, did not meet together, but it gave its members—including Galileo Galilei, who used to style himself “linceo” (lynx) on the title pages of his books—a sense of common enterprise. Galileo’s disciples established a closer-knit body, the Accademia del Cimento (1657–1667), under higher patronage (the Grand Duke of Tuscany and his brother, a cardinal) and with better resources (salaries, instruments, and a meeting place). Inspired also by Francis Bacon’s project of improving the arts and sciences through cooperative effort, the dozen or so members of the Cimento, “whose sole Design [was] to make Experiments, and Relate them,” published an important collection of their “trials,” *Saggi di naturali esperienze* (1667), as a corporate contribution, without attributing discoveries to individuals.



Louis XIV receives the Académie royale des sciences ca. 1670. The Observatoire royal is in the background.

No other academy in seventeenth-century Italy had such lavish support as the Cimento, although several had even higher patronage. Examples are the Accademia Fisico-matematica of Rome, founded in 1677 by a cleric, Giovanni Giustino Ciampini, and encouraged by a cardinal (later elected pope) and by Christina, the converted former queen of Sweden; and the Accademia degli Inquieti (ca. 1690–1714), founded by professors at the University of Bologna, later (when endowed by a private citizen and the pope) the nucleus of the Accademia delle Scienze dell'Istituto di Bologna.

A similar transformation had occurred in France in 1666 when Louis XIV's chief minister decided that the king needed royal academicians to map the realm, perfect astronomy, improve navigation, and keep France current in natural knowledge. The Académie Royale des Sciences came into existence with a handful of salaried members including distinguished foreigners, notably Christiaan Huygens. Reorganized in 1699 and again definitively in 1716, the Paris Academy became the exemplar of a learned body in the service of a great monarch. Its forty-four regular members were distributed into six classes, three "mathematical" (geometry, astronomy, and mechanics) and three "physical" (chemistry, anatomy, and botany), and into three ranks (pensionnaire, associé, and adjoint). Its standing secretary had the duties of composing a history of the Academy's work each year as a preface to the annual volume of original *mémoires* presented obligatorily by members and, in due course, of composing their obituaries, which, taken together, became a role model for aspiring contributors to natural knowledge. The Paris Academy set prize competitions, advised the crown, and occasionally sponsored special projects like excursions to determine the shape of the earth. Typically, however, its members did their work at their own expense and in their own rooms or with material and in space provided by other Parisian institutions.

Only a very few monarchs could copy the academy of the King of France. The first to try, the King of Prussia, acting under pressure from Gottfried Leibniz, proved too stingy; the academy he established in 1700 had an uncertain and impoverished existence until refounded by Frederick the Great on Parisian principles. Its new statutes of 1744 provided for four classes (experimental philosophy, mathematics, speculative philosophy, and literature), members divided by rank, and, like the Paris Academy, a variable number of nonresident "correspondents." It published its histories and memoirs in French and, again like its model, engaged distinguished foreigners, notably Pierre de Maupertuis and Leonhard Euler. The westernizing Peter the Great of Russia also had the ambition and wherewithal to create an academy of salaried savants, which he accomplished in St. Petersburg in 1724, without Russian members. Monarchs more modest than the rulers of France, Prussia, and Russia founded smaller academies on similar principles. In 1783 the King of Sardinia transformed a group that had existed since 1757 into the Académie Royale of Turin, at the trifling cost of a building and a budget, and in 1757 the Elector of Bavaria established the Akademie der Wissenschaften of Munich with a meeting place, operating expenses, and half a dozen paid "professors." Closed or proprietary academies of the Paris type placed particular emphasis on mathematics and its applications, which they did much to advance.

Meanwhile, larger academies free to choose their members and able to salary only two or three functionaries flourished. The prototype was the Royal Society of London (founded in 1662), which had nothing from its patron, King Charles II but a charter, a mace, and the right to call itself "royal."

Like the Accademia del Cimento, it took much of its rhetoric and purpose from Bacon. Its *Philosophical Transactions* constituted, with the *Mémoires* of the Paris Academy, the most important and reliable periodical literature of natural knowledge during the eighteenth century. Like the Paris Academy, the Royal Society set up commissions to investigate debated matters: the calibration of thermometers, the shapes of lightning rods, and the merits of mesmerism. Since the Society depended on the dues and influence of its fellows, it began by enlisting any interested gentlemen or distinguished foreigners and made no distinction of class or rank. During the seventeenth and most of the eighteenth centuries, the number of fellows elected for their social status or professional affiliation exceeded in number those chosen for their contributions to science. Among the latter were many instrument makers.

Several important academies formed on the pattern of the Royal Society in Britain during the eighteenth century: the Royal Society of Edinburgh (1783), a contribution to the consolidation of the United Kingdom as well as a recognition of the flourishing of natural philosophy in the north; the Manchester Literary and Philosophical Society (1781), which reflected the aspirations and discussed the technologies of the industrializing midlands; and the American Philosophical Society (1768), a venture in colonial Philadelphia that became a symbol of intellectual equality with Europe. Important European counterparts of the Royal Society included Kungl. Vetenskapsakademien of Stockholm (1739), which stressed technological problems of Swedish interest, and the Hollandsche Maatschappij der Wetenschappen of Haarlem (1752), which innovated by distinguishing "directors," who paid dues, from "scientific members," who did the work. Few of the many royal regional academies of France could do more than give out an occasional prize or publication. An exception, the Académie Royale des Sciences et Belles-Lettres of Bordeaux (1712), though it had fewer than twenty members at any time, had its own building, library, botanical garden, and instrument collection, all given to it by local philanthropists.

The division of labor in the republic of learning, according to which universities disseminated, and academies increased, knowledge, often created tensions between professors and academicians. Universities sometimes opposed the creation of academies, as the University of Leyden did that of the Hollandsche Maatschappij. The *modus vivendi* established by the Istituto di Bologna, whereby university and academy exchanged personnel, existed formally in only one other place during the eighteenth century. In 1752 the English Hanoverian government set up a Königliche Societät der Wissenschaften as an adjunct to the university it had established in Göttingen in 1737. A few of the professors ran the academy, which issued publications, including an influential review, the *Göttingische gelehrte Anzeigen*, read all over Europe.

The Bologna-Göttingen model did not become the route by which professors came to dominate the academies during the nineteenth century. Instead, professors added research to their duties. This development, which began at the end of the eighteenth century, accelerated under the transformation of higher education and academic life caused by the French Revolution.

The importance of academies in the advancement of natural knowledge declined as professors took them over. Two factors were chiefly responsible. For one, journals independent of academies came to dominate scientific communication. Traditional academies published only a small fraction of the millions of papers carried in scientific journals between

1800 and 1900. Academies found an important niche in publishing, however, by printing papers rapidly, for example, in the weekly *Comptes rendus* (begun in 1835) of the Paris Academy and in the monthly *Proceedings* of the Royal Society (begun in 1856). Owing to the revolution in communications effected by railroads and the International Postal Union, a professor could send reprints of an article from the unread proceedings of his local academy directly to those who needed to know.

The second factor that diminished the scientific role of learned societies was the confirmation of the research activity of professors and provision for it in the higher schools and universities. With the invention of scientific institutes and departments with their own laboratories and apparatus after the middle of the century, academies ceased to be the main locus for the presentation and criticism of new results, for peer review, or for the financial and rhetorical support of research. This trend continued briskly in the twentieth century with the creation of governmental and industrial research laboratories and central funding agencies. The number of competent research scientists active in 2000 greatly exceeded the number of members in the national and regional academies; and even though more places have been added, academies have long since been unable to meet the expectation implied by the epitaph from Dijon, that they could admit all worthy contributors to science.

The nineteenth and twentieth centuries saw the spread of national academies of the Royal Society type throughout the world and the invention of an important new type, represented by the Akademiia Nauk, successor to the Petersburg Academy. The Soviet Union chose to funnel state support for research and advanced training in science through the Akademiia and its regional dependencies, which thereby captured functions that further west belonged to universities and government laboratories. A senior academician in the Soviet Union had useful perquisites and often enjoyed political influence or protection. Similar arrangements held elsewhere in the Soviet bloc.

Most academies now primarily serve organizational and honorific functions. They are nodes in national and international networks that promote research or outreach beyond their own memberships. The international coupling of major academies began in the nineteenth century as the International Association of Academies. Headquartered in Berlin, it oversaw such projects as the Carte du Ciel and the International Catalogue of Scientific Literature. During World War I, the Paris Academy, the Royal Society, and the U.S. National Academy of Sciences (through a subsidiary it set up called the National Research Council) organized science for military purposes. After the war the allies revived the cooperation of academies under an International Research Council, which at first excluded institutions belonging to the defeated Central Powers. The international network survived World War II in the form of the International Council of Scientific Unions (ICSU). A regional subset of these academies, the European Federation of National Academies of Sciences and Humanities (ALLEA), declares the objectives of its thirty-eight members to be to "promote excellence in science and scholarship . . . value and promote independence from ideological and political interests . . . [and] serve society with advice on science policy." They differ from their forerunners in asserting independence from the regimes that support them.

Although the national academies do advise governments when asked, and also award prizes and research grants (if any), and do what they can to improve public understand-

ing of science, their main function now is honorific. Election to a major scientific academy is itself a distinction. The leading modern institute in the bestowal of prizes is an old academy, that of Stockholm, which exerts a worldwide influence far beyond the scientific work it fosters by giving the Nobel awards in physics and chemistry. Carrying the tendency toward absurdity, "academies" with virtually no purpose but to elect members multiplied in the twentieth century. Examples are the Academia Europaea (founded in 1988) and the Académie International d'Histoire des Sciences (1928). These organizations differ little in function and notoriety from the Baseball Hall of Fame.

J. L. HEILBRON

ACCELERATOR. During the twentieth century physicists developed increasingly powerful artificial means to produce very high-energy particles to transform or disintegrate atoms. At the end of World War I, Ernest Rutherford used alpha particles from naturally occurring sources of radiation to transform nitrogen into oxygen. He called for the development of more energetic sources of charged particles for nuclear experiments. Two of his students, John D. Cockroft and Ernest T. S. Walton, completed the first successful particle accelerator at the Cavendish Laboratory in Cambridge in 1932. By accumulating a potential of hundreds of thousands of volts, Cockroft and Walton accelerated protons to energies sufficient to disintegrate the nuclei of light elements. Owing to the repulsion between nuclei and protons, and the difficulty of creating and maintaining high potentials, their machine could not transform heavier elements.

Physicists soon turned to other means to accelerate particles. In the United States, Ernest Lawrence's magnetic resonance accelerator (the cyclotron), which applied energy to protons or deuterons in successive small steps rather than, as in the Cockroft-Walton machine, in one large jump, provided bombardments able to transform almost all nuclear species. His linear accelerator used the same principle of resonance acceleration to propel heavier nuclei. Another American, Robert Van de Graaff, returned to the one-jump method by a technique that allowed the accumulation of up to about ten million volts on a spherical conductor. The Van de Graaff, cyclotron, and linear accelerators were used at many universities and research institutes in the 1930s to explore the new field of nuclear physics. Financial support for the development of particle accelerators came largely from medical philanthropies. They hoped their high-voltage X rays, neutrons, and other particles as well as the artificially radioactive products of their interactions with other substances would be more effective against cancer and other diseases than the natural radiations from radium and other substances.

Lawrence was especially successful in generating support for his cyclotrons. The parameter most often employed to indicate their power—the diameter of the pole pieces of the magnet that retained the particles in their spiraling orbits as they accumulated energy—grew from a few inches to sixty. The increase in size gave a monumental increase in the energy with which the particles escaped from the magnet—from a few hundred thousand to thirty-two million electron volts. In 1939 Lawrence received the Nobel Prize in physics for his cyclotron and work done with it. The consequent enlargement of his prestige helped him to convince the Rockefeller Foundation to give the money to build a giant cyclotron with pole pieces 184 inches in diameter. Intended to be the last and largest of all particle accelerators and, in that way, the counterpart to the 200-inch telescope the foundation

supported at Palomar, the 184-inch proved instead to be the first of a generation of much larger particle accelerators.

The cyclotron did not accelerate electrons because their loss in energy and increase in mass owing to acceleration made them unattractive for work at high energy. Nonetheless, in 1939 Donald William Kerst invented a "betatron," which produced electrons or energies useful in nuclear investigations. After the war linear electron accelerators became competitive with proton accelerators for some purposes, and physicists turned the intense radiation of electrons maintained in circular orbits to advantage in "synchrotrons" whose "light" could be used in materials science and other applications.

The discovery of nuclear fission in uranium in 1939 provided a new role for particle accelerators and nuclear physicists. Cyclotrons at Berkeley and Los Alamos produced the first samples of plutonium, and cyclotron principles underlay the electromagnetic separation of isotopes in large banks of "calutrons" (after California University) that separated the fissile isotope of uranium for use in the first atomic bombs. Although other techniques eventually proved more efficient, these wartime successes opened the door to federal funding of nuclear physics by the Manhattan Engineer District and its successor, the Atomic Energy Commission.

The completion of the 184-inch cyclotron as a synchrocyclotron in 1946 was the first successful application of the synchrotron principle discovered by Edwin M. McMillan and Vladimir I. Veksler during the war. This principle enabled designers to accelerate particles in tight bunches by changing the frequency of the accelerating fields in step with relativistic changes in the mass of the particles. A series of accelerators built throughout the second half of the century, ranging from Brookhaven's 'Cosmotron' to the Tevatron, which produces trillions of electron-volts, incorporate the synchrotron principle and advances in magnetic technique that permit the confinement of the beam of accelerating particles to a narrow, evacuated pipe of fixed radius. The only link to the size of these machines is financial. The first version of CERN had a diameter of 200 meters; the one now under construction there extends to 27 kilometers. The largest current machine in the United States, at Fermilab, has a circumference of four miles, within which a herd of bison graze.

The linear accelerator also developed rapidly after World War II. At Berkeley, Luis Alvarez invented a type for protons using war surplus radar equipment. His student Wolfgang Panofsky applied the scheme to electrons at the Stanford Linear Accelerator (1962). Discoveries of new elements and particles by particle accelerators led to Nobel Prizes as well as increasingly larger accelerators in the United States, western Europe, and the Soviet Union. The prestige and power of these machines made them political as well as physical icons. Only after the end of the Cold War did the enormous cost of accelerators prompt the United States to withdraw from the competition by canceling the Superconducting Super Collider.

ROBERT W. SEIDEL

ACOUSTICS AND HEARING. Acoustics, the science of sound, falls at the intersection of several fields, including mechanics, hydrodynamics, thermodynamics, and electromagnetism. Scientific interest in sound also derives from human hearing and hence involves physiology and psychology. Also, acoustics engages fields outside science such as music and architecture. A distinct field of acoustics, including but not limited to hearing, gradually emerged from this disparate background in the eighteenth and nineteenth

centuries, aided by the use of quantitative apparatus to produce and detect sound and the mathematical analysis of the results.

Ancient and medieval philosophers of nature studied acoustics mainly as a means to understand music. Mathematical theories of music dated at least to the Pythagoreans, who identified musical intervals as ratios of whole numbers and related musical pitches to lengths of vibrating strings. Although a few ancient writers speculated on the wave nature of sound and the propagation of compressions, Arabic and European natural philosophers through the Middle Ages and Renaissance continued to study acoustics only as part of music theory, if at all. In the early modern period, natural philosophers began to undertake systematic experiments and to extend their investigations to sound in general. Experiments with vibrating strings led Galileo Galilei to posit the relation between pitch and frequency, elucidated around the same time by Giovanni Benedetti and Isaac Beeckman, and also to suggest that pitch depended on the tension and diameter of the string as well as its length. Marin Mersenne in the early seventeenth century used very long vibrating strings, some over one hundred feet long, to arrive at a quantitative relation between pitch and frequency. Mersenne also measured the speed of sound, as did his contemporary Pierre Gassendi, who asserted that soft and loud sounds traveled at the same speed.

The scientific academies that sprang up later in the seventeenth century would make the speed of sound a prime program. Around the same time, experiments with improved air pumps, beginning with Otto von Guericke and extended by Robert Boyle and Francis Hauksbee, convinced natural philosophers that sound did not travel in a vacuum. Experiments on the speed of sound tested in particular the theory of Isaac Newton, whose work on fluid mechanics in the *Principia* included acoustics. But Newton arrived at a figure for the speed of sound, based on the pressure and density of the medium, at odds with contemporary estimates. Mathematicians in the eighteenth century, notably Leonhard Euler, Jean d'Alembert, and Joseph Louis Lagrange, extended Newton's analytical mechanics and pneumatics to explain the discrepancy between theory and measurement, and Pierre-Simon, Marquis de Laplace, Jean-Baptiste Biot, and Siméon-Denis Poisson at the start of the nineteenth century succeeded by suggesting that the passing sound wave heated the medium.

The quantification of acoustics accelerated in the nineteenth century, driven by the use of laboratory apparatus such as tuning forks, vibrating plates, and sirens to produce standardized tones, and sounding boards and the stethoscope to detect them. The new instruments helped bring acoustics into the realm of precision physics and also indicated the increasing quantification of physiology. Hermann von Helmholtz combined knowledge of the physiology and physics of sound in his synthetic treatise *On Sensations of Tone* of 1862, which confirmed that the ear analyzes periodic sound waves into Fourier sums of simple harmonics and predicted the existence of nonlinear summation tones. John Tyndall helped bring Helmholtz's work to English-speaking audiences, elaborating it with his own experiments and generalizing beyond Helmholtz's particular interest in music. Lord Rayleigh then provided a systematic mathematical analysis of sound in his *Theory of Sound* of 1877-78; although Helmholtz provided mathematical details in appendices to his works, he had kept the main text nonmathematical. Rayleigh's two-volume work analyzed diverse phenomena of

sound based on the vibration of air, liquids, and gases and of solid strings, plates, and rods under various perturbations; the books completed the edifice of classical acoustics.

New problems and programs were meanwhile emerging from the development of electromagnetism and its application to acoustics. Alexander Graham Bell, familiar with Helmholtz's research and inspired by his own work with deaf students, invented a means for transmitting speech over wires, called the telephone. Bell faced several coclaimants for the invention and strong competition for its development, including an improved system designed by Thomas Edison. Edison in the meantime invented the phonograph, the foundation for the recording industry. The development of radio further spurred the invention of microphones, loudspeakers, amplifiers, vacuum tubes, and oscillators by the burgeoning electrical industry. Industrial engineers also agreed on an international standard for the intensity of sound, the decibel. Magnetostriction, piezoelectricity, and acousto-optics, three more developments of the late nineteenth century, would also provide new ways to produce and detect sound. Electroacoustics opened up a rich new field for the study of sound in the twentieth century.

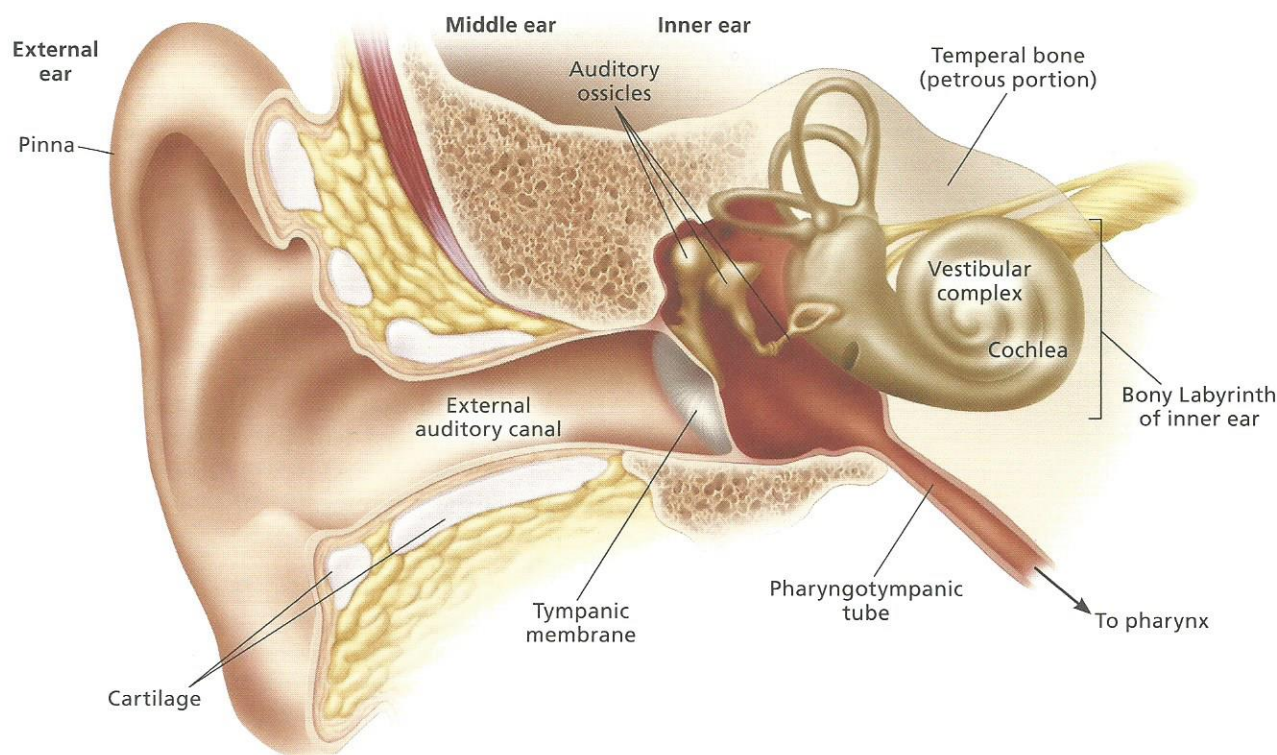
Electroacoustics also helped to transform architectural acoustics, the study of which dated to the ancients—the Roman architect Vitruvius wrote on the acoustics of theaters in the first century B.C.—and was extended in the seventeenth century by the Jesuit polymath Athanasius Kircher, among others. Around 1900 Wallace Sabine revived the subject with his work relating reverberation times to the volume and building materials of rooms. The introduction of electroacoustic technology, along with new sound-absorbing building materials, provided a means to active control of sound inside buildings, and in 1930 Carl Eyring revised Sabine's results to accommodate the new acoustic environments.

Sound does not just travel through air. The use of submarines in World War I spurred efforts to develop ways to detect them, which soon focused on sound. The subsequent development of sonar for submarine warfare provided much support of acoustics research and also new tools for marine biology and oceanography. Sound also travels through matter, and ultra-high frequency sound, or ultrasound, became an important probe for solid-state research and found application in industrial materials and in medicine in the second half of the twentieth century.

PETER J. WESTWICK

ADVANCEMENT OF SCIENCE, NATIONAL ASSOCIATIONS FOR THE. During the seventeenth century, naturalists and philosophers emphasized scientific communication among themselves and sought venues for public demonstrations of scientific achievement. Francis Bacon shifted discussion toward what he identified as the “advancement of learning” through human design and proposed a hierarchical model of organization in his fictional work, *The New Atlantis* (1627). Advancing knowledge became associated not only with individual genius but with organizations like the Royal Society of London (1662), which sponsored research activities and publications to share new knowledge. Local voluntary societies provided repositories for specimens, artifacts, and instruments important for advancing research, but these proved expensive to maintain and of benefit primarily to a local membership.

By the nineteenth century, transportation networks of canals and railroads facilitated travel while public interest in science was creating popular audiences and paying occupations for scientists just as cultivators of natural science began to feel a sense of community. German-speaking physicians and scientists, who also felt political isolation, were the first to organize on a national level. Lorenz Oken proposed the



Sound collected by the external ear causes the tympanic membrane (center right) to vibrate; the vibrations are transmitted to the fluid-filled cochlea (the spiral structure); minute hairs lining the cochlea generate the nerve impulses that activate the brain.

foundation of the Gesellschaft Deutscher Naturforscher und Ärzte (GDNA), modeled loosely on a Swiss organization, in 1822. The GDNA grew quickly, met in a different city each year, and facilitated communication among its members.

Several British attendees at the German meetings, who perceived a decline of science in England, Scotland, and Ireland, rallied colleagues by letter and publication to attend a meeting in York, "the most central city for the three kingdoms," in 1831. The resulting peripatetic British Association for the Advancement of Science (BAAS) proved highly successful at attracting public audiences. It quickly became a forum where physical, natural, and social scientists could discuss matters of scientific content and policy, capacities that proved particularly attractive to the visiting North Americans who subsequently established the American Association for the Advancement of Science (AAAS), founded in Philadelphia in 1848. Positioned to enhance the professional ambitions of leaders and serve as advocates for their plans, the AAAS members conducted business at their annual meetings, published proceedings, and created committees to look into special topics from terrestrial magnetism to science education. As a scientific forum the AAAS allowed disputants the opportunity to argue from evidence before peers and to wrestle with such complicated issues as chemical nomenclature and universal species taxonomy. Over the next half century, France, the Netherlands, and Belgium established similar organizations and the movement spread into increasingly independent colonies seeking industrial and government sponsorship for scientific and technological activities. The Italians reinvented a *Riunione degli Scienziati Italiani* (1839) under various titles over the next century as well.

The BAAS leaders extended membership privileges to British colonials and held five overseas meetings in colonies between 1884 and 1914. The resultant linkages advanced scientific dialogue but sustained international hierarchies as well. Public lectures by distinguished scientists provided stimulus to local science, and sometimes local scientists and visiting experts collaborated on research projects, but inevitably much of the scientific data, and credit, returned home at the conclusion of collaborations. That, at least, was the case for anthropology in Canada, where important early work on northwestern Native Americans and an ethnographic survey of tribes provided unprecedented, immediate opportunities for Canadian amateurs but left no national school in anthropology when the experts went back to England. Far from Britain, the Australia and New Zealand Association for the Advancement of Science (1888) began to link regional scientists and publicize their work. During the first quarter of the twentieth century similar initiatives came in India, South Africa, Hong Kong, and other colonial outposts.

In the twentieth century countries aspiring to democracy as well as technological and scientific progress initiated associations to advance science. Government sponsorship, rather than grassroots voluntarism, became common; for example, the Japan Society for the Promotion of Science (1932) became a channel for funds to large, expensive research facilities. After World War II the model seemed promising for aspiring nations like Brazil, where the Brazilian Society for the Advancement of Science grew from scientific initiatives that persuaded the government to provide financial support. Scientific members, however, found themselves politicized and, indeed, in conflict with policies of a military regime during turbulent times. Nationally based societies, regardless of their financial autonomy, inevitably worked within and through their home political systems, carefully

balancing professional norms as they lobbied for scientific budgets, educational policies to support science, and independent peer review for evaluation of research.

National societies varied considerably as they pursued the goal of advancing science. In Britain the early success of the BAAS correlated with the status of scientific activity and high visibility of prominent scientists like Charles Lyell, and was sustained by its outreach in provincial areas to enhance science education. In the United States, members relied on the AAAS to establish a forum for widely dispersed scientists, to maintain links among scientists across the increasingly distinct scientific specialties, and to advocate science to state and federal governments. In the twentieth century the AAAS published *Science* magazine, under editor James McKeen Cattell, the leading journal across the sciences with the largest international readership in the early twentieth century. In this respect the AAAS outdistanced the BAAS, which does not run the leading general British science journal, *Nature*.

The AAAS, with affiliates from most major professional societies, moved to rooms in the Smithsonian Institution until it built its own permanent headquarters in Washington, D.C., where it also reported on research and developments in federal agencies and budgets. By the late twentieth century the AAAS had an administrative and editorial infrastructure whose capacity to report on scientific developments was international, while specific programs in the organization concentrated on science education, promoted gender and racial diversity, and responded to ethical issues raised by advances in science, technology, and medicine. National societies produced a sense of identity even as they provided vehicles for international exchange of publications, visiting status to foreign attendees at meetings, and occasional collaborations.

Efforts to link these national organizations in a formal way have had mixed success. Shortly after World War II, in 1950, the United Nations Educational, Scientific, and Cultural Organization (UNESCO) sponsored an International Meeting for Associations for the Advancement of Science, but the effort faded from lack of support by the well-established organizations like the AAAS and BAAS. An International Federation of Associations for the Advancement of Science and Technology founded in the 1990s persisted, suggesting that the rootedness in particular settings has allowed many national associations to be highly successful but that emphasis on national needs and interests constrained systematic cooperation, at least before the advent of the Internet.

SALLY GREGORY KOHLSTEDT

AFRICA. The history of science in the diverse continent of Africa is best dealt with under four headings: precolonial science in Islamic North Africa, precolonial science in animist Sub-Saharan Africa, European-based colonial science, and science in independent African nations.

Precolonial North Africa

From the eighth century on, North Africa had close ties, culturally and scientifically, with neighboring Islamic regions. From the ninth to the thirteenth century, scholars in Egypt looked to the Baghdad caliphates. In the Maghreb, stretching west of Egypt to Morocco, scholars had close links with Islamic Spain, which saw a flowering of culture and learning through the twelfth century.

For a time, mathematics, astronomy, and medicine flourished under the patronage of the sultans. However, by the fifteenth century, North African Islamic movements

had nearly extinguished these intellectual inquiries. Legal scholars and theologians came to view rational study of nature as irrelevant and potentially heretical. Moreover, mystical Sufi orders became widely popular among the people. The role of patient empirical and rational investigation of nature as a way to learn about God was subordinated far below the revelations of the Quran and mysticism. Centers of Islamic learning, such as al-Azhar of Cairo, the Zaituna of Tunis, and the Qarawiyyin of Fez no longer supported teachers of natural philosophy. Those who sought such teachers had to search for dwindling numbers of isolated scholars.

What remained was routine work, such as compilation of astronomical tables, which continued to the eighteenth century. Because it was needed to determine the *qibla* (the direction to Mecca) and the five daily times of prayer, astronomy had a privileged status. Even so, it became suspect because of its association with astrology, which was often practiced in the courts of the sultans. Increasingly, folk astronomical methods determined the *qibla* and times of call to prayer in place of the earlier complex, mathematical astronomy. Mathematical usage narrowed to practical matters such as the calculation of inheritances. Medicine too declined; only the vestiges of early Islamic medical science survived. In its place, a folk medicine, which continues to be practiced today, brought together Yunani (Greek) medicine derived from Galen and mystical prophetic medicine associated with the sayings of Mohammed. By the time of European colonization, innovative work in mathematics, medicine, and natural philosophy had long disappeared.

Nor did such work survive along the southern “shores” of the Sahara, the Sahel, a cultural outpost of North Africa. North Africans brought to the Sahel writing and formal education for teaching the Quran. By the sixteenth century, Timbuktu had emerged as a major center of Islamic learning, where mathematics of inheritance was taught, but not natural philosophy. By then other leading Islamic universities, such as the Qarawiyyin and the Zaituna, had already jettisoned nonreligious studies.

Precolonial Sub-Saharan Africa

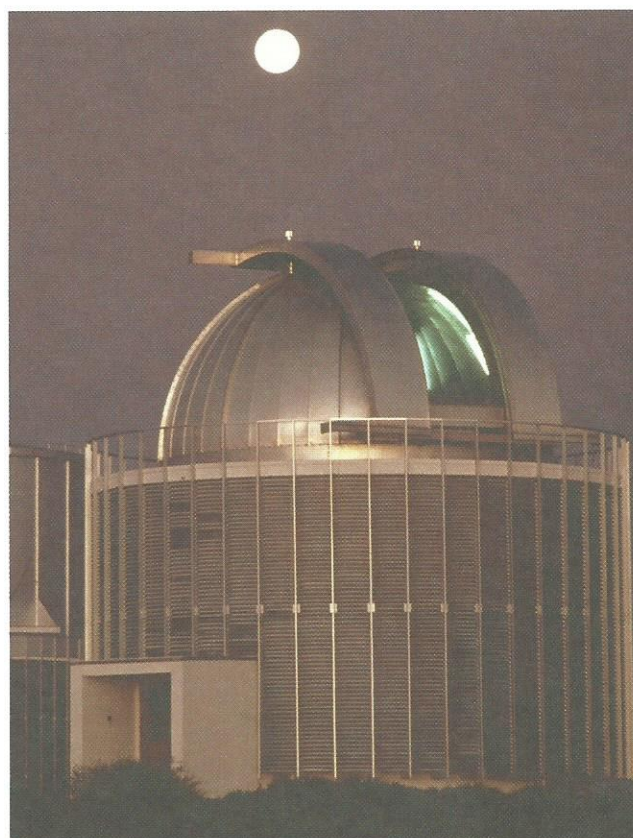
South of the Sahel, traditional medicine and various technologies, including sophisticated iron and bronze metallurgy, flourished prior to European colonization. They did little, though, to point the way to anything resembling modern science. In the African worldview, the natural world was a realm of spirits approachable by sorcery. In this context, analyzing nature according to the rational, disinterested ideal of Western science was unthinkable. Smelting iron required placation of spirits. Traditional healers interpreted the spiritual, psychological aspects of the ill and their communities using mediation with the spirits (although they also turned to herbalists for remedies that had proven effective). Moreover, lack of written languages impeded the progressive accumulation of natural knowledge beyond the limits of oral traditions. Even after the arrival of Christian missionaries, animistic worldviews persisted.

The incursions of the Europeans further discouraged the appearance of science. Importation of European goods, such as weapons, iron, cloth, and glass, undermined traditional technologies. The consequences of the slave trade and warfare in some regions exacerbated the loss of indigenous technology. Traditional knowledge and skills dwindled yet further, sending the societies into cultural decline.

Colonial Africa

Napoleon's invasion of Egypt (1798–1802), with an accompanying body of scientists who studied the riches of its ancient past, marked the beginning of European scientific interest in Africa. The French began colonizing in earnest in Algeria in the 1830s by sending a large medical corps. Under the direction of the French military, doctors investigated Algeria's social structure and environment during their off-duty hours, exploring its potential as a colony. Several meteorological stations were set up extending deep into the Sahara. Also, a small observatory, established in 1858 to provide mariners with accurate time, became the Observatory of Algiers. From these beginnings, French scientific societies took root in North Africa, some of which carried out notable scientific work. For example, research in the Pasteur Institutes in Algeria and Tunisia led to the discovery of the carriers of malaria, typhus, and bubonic plague. These successes were rewarded with Nobel Prizes for Charles Louis Alphonse Laveran in 1907 and Charles Nicolle in 1928. Despite these achievements, the mother institutes in Paris tightly controlled scientific work. Following World War I, the French government founded the Ecole Supérieure d'Agriculture Tropicale and Institut de Médecine Vétérinaire Exotique to train colonial personnel in tropical agriculture and veterinary medicine. However, coordination of research in the colonies had to wait until the Vichy government of World War II formed the Office de la Recherche Scientifique Coloniale, which set long-term research and training goals.

In British colonies, scientific initiative, usually applied to agriculture and medicine, rested with the colonial governments, although fundamental research and training remained in Britain. In particular, research in tropical medi-



The South African Astronomical Observatory in Sunderland, South Africa, is a partner in many international research collaborations.

A

cine, most importantly work on parasitic diseases and their hosts, which initially fell to medical doctors in the field, centered in Britain with the founding of the London and Liverpool Schools of Tropical Medicine in 1899. After World War I, organizations covering different regions, such as the Forestry and Agricultural Organization of British East Africa and the West African Research Organization, promoted and coordinated research, largely in the agriculture of cash crops such as cocoa and palm oil. Scientific work shifted back to the colonies and regional centers with financing directly through the colonial governments.

Characteristically, European research in Africa was performed to benefit the colonialists or the mother country. Africans rarely advanced beyond assistants. Moreover, education for Africans imbued them with contempt of manual labor. Consequently they eschewed farming and generally did not apply their knowledge to make greatly needed improvements in agriculture.

Medicine had an important role in colonial Africa. The few doctors who went south of the Sahara were typically missionaries employing medicine as a proselytizing vehicle. They deprecated indigenous medical practice, promoting a decline in herbal medicine and spiritual healing. At the same time, the impersonal, antiritual character of Western medicine and the disdain of doctors for local traditions alienated much of the population.

The only part of Africa to develop leading, independent schools of research was the Union of South Africa. The Royal Observatory of the Cape of Good Hope, established in 1820 to study the southern sky, became a respected observatory under the Scotsman Sir David Gill (director, 1897–1907), a leading proponent for using photography to accurately measure stellar positions. South Africa became the favored site for southern hemisphere observatories owing to its dry highlands and political stability. Sir John Herschel, a celebrated English astronomer, travelled there in the 1830s and made extensive observations of nebulae in the southern skies. In the 1920s, three American universities, Yale, Michigan, and Harvard, each set up astronomical stations in the interior of South Africa to complement their observatories in the northern hemisphere. In the 1920s and 1930s, South Africa moved to the forefront of geological and paleontological research as well, largely through the work of Alexander du Toit, a Huguenot descendent. He was one of the greatest field geologists of the twentieth century and an early supporter of the theory of continental drift, for which he accumulated an impressive amount of evidence. During the same period, research on ancient ancestors of humans began to flourish in Africa with the discoveries of fossils of *Australopithecus africanus* by the South Africans Raymond Dart and Robert Broom. Another field in which South Africa has made a mark is botany. Of the botanical gardens that exist in several African countries, the Kirstenbosch gardens of South Africa (established in 1913) are the largest and most ambitious, with extensive programs devoted to saving endangered plant species.

Independent Africa

Immediately after independence from the colonial powers, which had occurred for most African countries by the mid-1960s, the new governments typically considered support of scientific research unnecessary. Building a national research capability was often deemed to consume too much time and money for young nations with limited resources; besides, the argument went, any research needed could be acquired from the former colonizing countries. On the other

side of the coin, the most scientifically advanced country on the continent, South Africa, exploited anthropology and psychology to justify apartheid.

By the late 1960s, African governments began to recognize the need to generate their own scientific research and technological development. Through several conferences held with African governments, such as the International Conference of the Organization of Research and Training in Africa in Relation to the Study, Conservation and Utilization of National Resources (1964), the United Nations played a major role in changing local attitudes toward science and technology. UNESCO has reinforced the idea with dozens of missions to African countries promoting science and technology.

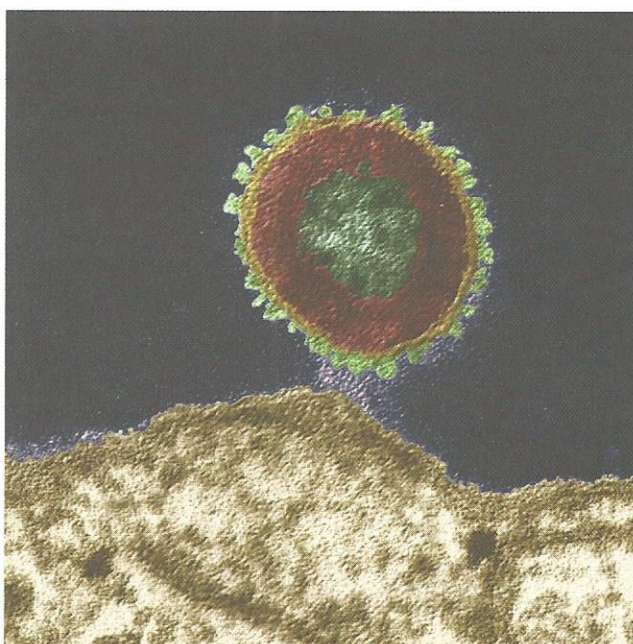
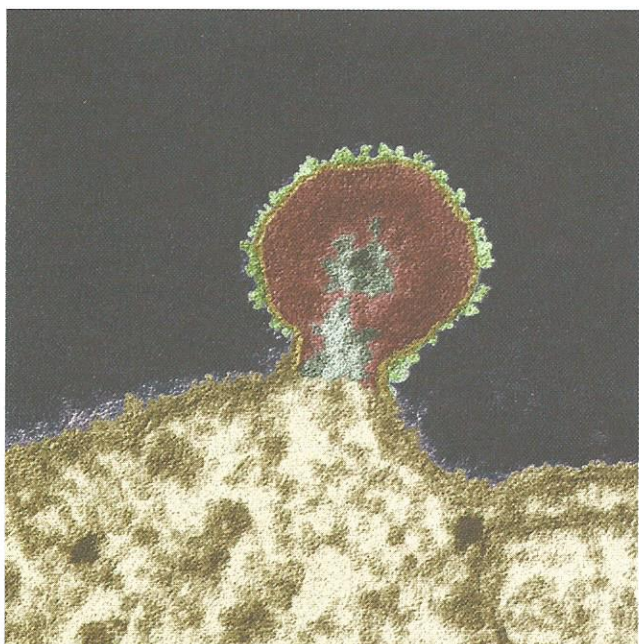
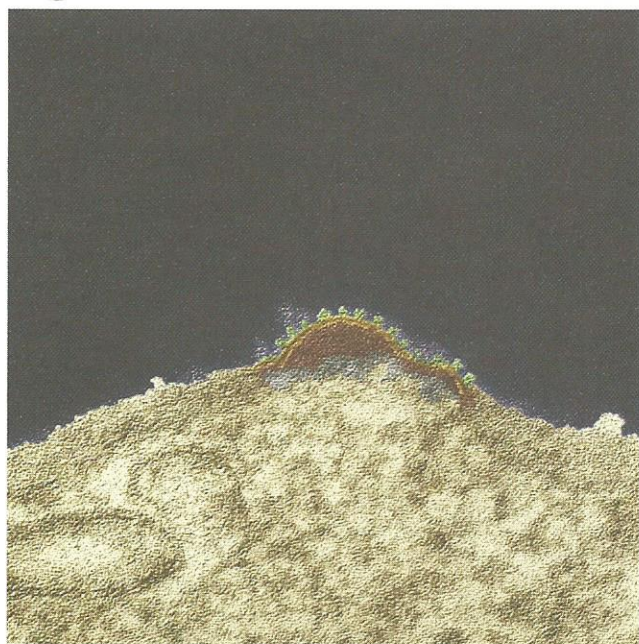
The hurdles are high. Cash-strapped government efforts often lead to routine, uncoordinated, understaffed, and unproductive investigations. African countries face serious shortages of scientists. Many of the brightest students study overseas and remain there. The African universities, having few resources, cannot supply the needed body of scientists. Overwhelmed by increasing enrollments and decreasing funds, the universities do little research. The bulk of research takes place in institutes headed by African scientists and financed by international organizations or governments. For example, the Kainji Lake Research Institute in Nigeria searches for new viral outbreaks, such as Lassa and Ebola fevers.

Africa has a choice between adopting Western science exclusively to solve its problems and bridging the gap between Western and indigenous, traditional approaches. In some countries, Western and traditional medicine are merging into systems to care better for the people. Many Africans today regard traditional medicine as a positive force that can complement the advantages of Western practices. This fresh outlook may help encourage a science in Africa for solving African problems and building the African future.

ROBERT DALE HALL

AIDS. Acquired immune deficiency syndrome (AIDS) was recognized in 1981 as the condition underlying a cluster of several different diseases, notably a type of pneumonia and certain cancers, afflicting certain demographic groups—in the United States, homosexual men in particular. A group headed by Luc Montagnier at the Pasteur Institute in Paris and another under Robert Gallo at the National Cancer Institute in Bethesda, Maryland, sought the cause of the syndrome. Both suspected that the disease agent was a retrovirus similar to the two viruses then known to produce leukemia in human beings. The two groups cooperated. In 1984 both isolated the culprit retrovirus from the tissues of AIDS victims, and characterized it using both serological and molecular techniques. It is much disputed whether Gallo's laboratory succeeded independently of Montagnier's or whether it isolated the retrovirus from material provided by Montagnier's and then failed appropriately to acknowledge the source.

Wholly different from the two leukemic retroviruses, the AIDS agent was soon dubbed the human immunodeficiency virus (HIV) because it attacks the immune system. Scientists in many laboratories learned that HIV targets the white blood cells called "T cells" (because they come from the thymus), particularly the major fraction of them that bristle at their surfaces with a molecule termed CD4 and that direct the body's immune response. In AIDS patients, the number of T cells with CD4 molecules is sharply reduced, steadily compromising the body's ability to mobilize against one or more wasting diseases.



Colored transmission electron micrograph of an AIDS virus (red/green) budding from the surface of a T-lymphocyte white blood cell. The new virus particles erupt to infect other T-lymphocytes.

HIV enters the body mainly by transfusion with infected blood, intravenous drug injection with infected needles, or unprotected sexual intercourse with an infected person. The Montagnier and Gallo groups both quickly developed and patented different blood tests that detect the presence of the virus from antigens produced against its several parts by the body's immune system. A dispute between the governments of the United States and France over which group properly had rights in them was resolved by a compromise in 1987 that divided the revenues. Blood-screening tests greatly diminished the risk of infection to people who depended on blood transfusions, notably hemophiliacs.

Public officials, especially in the United States, were initially skittish towards dealing with AIDS because of its strong link to homosexuality. However, coming to recognize that it posed a major threat to public health, they substantially increased public funding of AIDS research and urged sexual abstinence, monogamy, and the use of condoms to halt the

spread of the disease. The search for a vaccine against AIDS has so far proved fruitless. However, during the 1990s several biotechnology firms developed pharmaceuticals that inhibit the reproduction of HIV. Daily cocktails of these drugs have turned HIV infection into a chronic rather than a deadly condition for those who can afford the treatment. Between 1993 and 1997, the incidence of AIDS in the United States fell by almost 50 percent, to about 22 per 100,000 people. But many live in regions where preventative measures are unknown or ignored, and the cocktails unaffordable. Across the globe at the end of 2001, an estimated 40 million people were infected with HIV, and in sub-Saharan Africa AIDS was epidemic.

DANIEL J. KEVLES

ALCHEMY. Scholars can make solid arguments for the rise of alchemical ideas in ancient China or Persia, but most identify its birthplace in the Hellenistic cultural period, probably in

Egypt under the Ptolemaic Kingdom and the early Roman Empire. The sort of alchemy practiced there was born from a mix of Aristotelian theories of matter; Hellenistic religious philosophies such as gnosticism, hermeticism, and the mystery cults; and various ancient metallurgical and chemical techniques. The first practitioners probably were a secretive group or sect, perhaps Hellenized Egyptians in Alexandria.

The earliest definitely known alchemical writer, Zosimus, lived in Alexandria about 300 A.D. and wrote a handbook or encyclopedia of his craft. The allegorical and allusive character of the writing has made its interpretation problematic. Zosimus's book forms a part of the Greek alchemical corpus, a collection of mostly anonymous or pseudonymous writings first assembled a hundred years or more after Zosimus, and known today from a handful of medieval Greek copies. Zosimus and other Greek alchemists aimed to produce valuable metals from less expensive materials, prepare pharmaceutical remedies, and undergo philosophical or religious purification. Important materials in the craft included sulfur, mercury, arsenic, and electrum (a gold-silver alloy).

Leading Islamic scholars, who derived the craft from the Greeks, practiced it, especially in the tenth and eleventh centuries. The number of modern chemical terms that derive from Arabic—alchemy, alkali, alcohol, elixir, and naphtha, for example—indicate the importance of this period to science. The most famous Arabic alchemist, Jabir ibn Mayyan, supposed to have lived in the early ninth century, seems in fact to have

been a mystical Islamic sect that wrote pseudonymously a hundred years after Jabir's death. The celebrated philosophers al-Razi (Rhazes) and Avicenna (Ibn Sina) both pursued alchemy. A chief idea of medieval Arabic alchemy held that metals were formed of sulfur and mercury in various proportions, and that altering the proportions in a given metal could change its type, even from lead to gold. Not every alchemist, however, believed in the possibility of such transmutations.

During the twelfth century, scholars in the Christian West translated the ancient Greek philosophical and scientific corpus from Arabic into Latin; among these were works on alchemy elaborated by the Muslims. Albertus Magnus and Roger Bacon occupied themselves, among much else, with alchemical pursuits. A slightly later figure (fl. ca. 1300), perhaps the most important Western alchemist of the Middle Ages, called himself Geber. (Until about a century ago, scholars regarded "Geber" as the Latin form of "Jabir," and Geber's books as Latin translations of the *Suppositions Jabir*; they now regard Geber as a pseudonym of an unidentified Latin scholar.)

In Geber we first see unequivocal evidence for the use of concentrated mineral acids, with proof of distilled alcohol coming around this same period. These new substances, made possible by technological innovations, especially the more efficient cooling of distillates, dramatically altered the operational repertoire of chemists and alchemists. Three fourteenth-century Catalonians—Arnald of Villanova, Ramon Lull, and John of Rupescissa—incorporated these innovations into alchemy. Among other changes, the position of mercury in alchemical manipulations became more central. Despite this activity, interest in alchemy declined, only to reappear with renewed vigor in the Renaissance.

Alchemical ideas grew out of the cultures of which they were a part. Consequently, Greek, Arabic, late medieval, Renaissance, and early modern alchemical traditions each had distinctive characteristics. The craft also diffused within each cultural tradition. Some alchemists devoted themselves to practical tasks: pharmaceutical preparations; techniques of smelting, assaying, and metalworking; or manufacture of dyes and other chemical substances of commercial importance. Other alchemists sought to produce gold from base metals, or the "elixir of life" that would cure any disease. Still others regarded their discipline as an ethical or religious doctrine. Just as one could cure a metal of its imperfections to produce eternally incorruptible gold, or cure a human body of its imperfections to produce eternal life, so also, with the right discipline and approach, could one cure one's soul of its flaws and achieve salvation in heaven. In Renaissance Europe, the hermetic arts experienced a resurgence along with the humanist movement. Alchemy was regarded as one of these secret sciences, and many practitioners were powerfully influenced by Christian mysticism.

A leading early sixteenth-century alchemist was Theophrastus Bombast von Hohenheim, known as Paracelsus. Paracelsus's philosophy mixed gnosticism, cabalism, astrology, magic, and heterodox Christianity, and he gained significant fame (or notoriety) as a peripatetic iconoclastic physician. He championed the role of alchemically prepared mineral remedies, and certain of his treatments—mercury for the new scourge of syphilis, for instance—were doubtless efficacious. Paracelsus's emphasis on chemicals in pharmacy and medicine, called iatrochemistry or chemiatriy, influ-



Paracelsus, that is, Theophrastus Bombastus von Hohenheim (1493–1541), from a celebratory broadsheet of the sixteenth century

enced later figures. Lively controversies over his approach still raged around 1600.

Other sixteenth- and seventeenth-century figures expressed doubts about the possibility of alchemical transmutations and cures, and gradually the hermetic influence declined in Europe. Two of the chief heroes of the Scientific Revolution, Robert Boyle and Isaac Newton, were active in alchemical pursuits, which provides a measure of the staying power of these ideas. Through most of the seventeenth century, however, no one distinguished between scientific “chemistry” and “alchemy” (eventually viewed as pseudo-science); both words existed, but each indicated the same set of diverse activities, practical and mystical. Only during the 1680s did the popular chemical textbook of Niccolao Lavey open the first of a series of attacks on alchemy as fraudulent. Early Enlightenment thinkers then banished “alchemy” to the discredited category of occult doctrines while restricting the word “chemistry” to the science we know today.

A. J. ROCKE

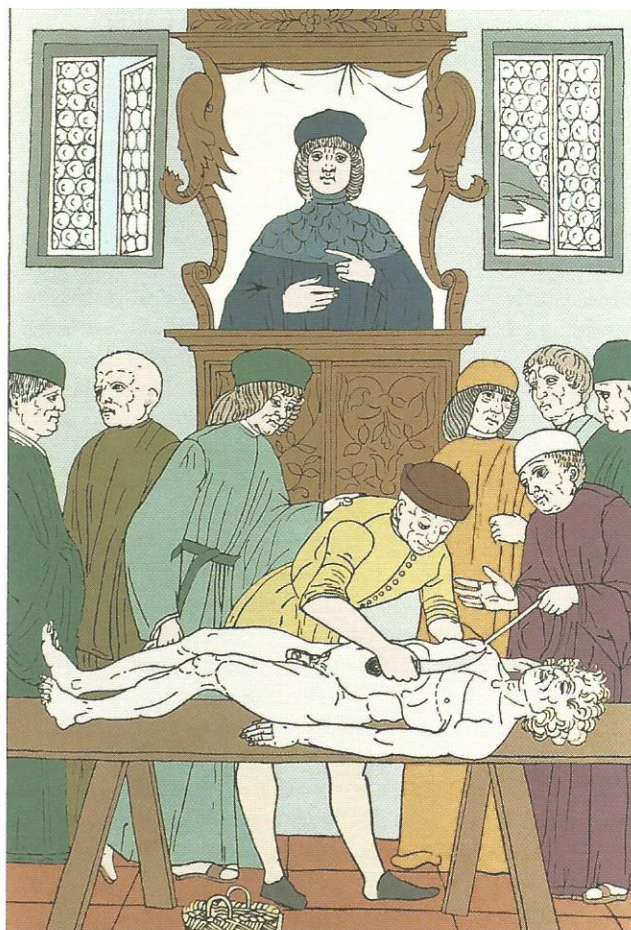
ANATOMY. In modern parlance, anatomy is synonymous with the dissection of a human or animal body. In history, however, the term referred more broadly to a metaphor and a model, a method and a practice. In the early modern period, “anatomy” implied an analysis in the sense of taking something apart—not necessarily a body—to its fundamental components. In the early seventeenth century, Francis Bacon advertised “an anatomy of the world,” and in 1621 Robert Burton published his *Anatomy of Melancholy*.

Through the eighteenth century, anatomy referred both to the act of dissection and to its subject, the human or animal body. In this era, the act referred to both living and dead bodies, although later anatomy came to denote dissection of the dead. In addition, anatomical models, such as wax ones used for teaching purposes, as well as dried and preserved specimens, came under the rubric. Many anatomy cabinets existed to teach students basic structures before they witnessed an anatomy lesson and to reinforce their knowledge afterwards.

Modern anatomy began with the work of Andreas Vesalius and his contemporaries in the sixteenth century. By means of human and animal dissection and animal vivisection, they explored and analyzed the structure of the human body. At almost the same time, however, some anatomists began to find the animal body of interest in itself, and comparative anatomy developed alongside human anatomy.

Anatomy and physiology were not distinct disciplines until the nineteenth century, and early modern anatomists explored both. William Harvey, for example, explained both the form and the function of the human heart and also compared the hearts of different species. Researchers in the seventeenth and eighteenth centuries dissected and vivisected many animals both to explore morphology and, especially, to answer questions about function. Because of the variety of animals they used, much of the work of men such as Marcello Malpighi was broadly comparative. A group of some of the first members of the Paris Academy of Sciences, including Claude Perrault and Joseph-Guichard Duverney, used the resources of the Jardin des Plantes and the menagerie at Versailles to compile their important *Mémoires pour servir à l'histoire naturelle des animaux* (1676), which notes morphological similarities but without an underlying theory of type.

Public anatomy, in which a human cadaver (and usually several live and dead animals) was dissected before an audience, flourished in the seventeenth and eighteenth centu-



Anatomy lecture and dissection from Joannes de Ketham, *Fasciculus medicinae* (1495)

ries. While such exhibitions taught medical students about the form of the human body, they also attracted members of the general public who found the spectacle entertaining and the contemplation of mortality edifying. The decline of public anatomy at the end of the eighteenth century revealed changing sensibilities as well as a recognition that such dissection could no longer reveal anything new.

Municipal authorities usually allowed one or two cadavers of executed criminals per year for public dissection, although the number varied according to local custom. Those who gave multiple courses, or wished to do research, usually resorted to grave robbing. Vesalius bragged about his skill at pilfering corpses. Two centuries later Duverney bribed the grave-digger at the Hotel-Dieu in Paris to provide him with bodies. In England, the so-called Murder Act of 1752 gave the College of Surgeons first right to the bodies of executed criminals, but other researchers and lecturers continued to rely on “resurrection men.” In Edinburgh in the late 1820s, an entrepreneurial pair named Burke and Hare murdered indigent people and sold their bodies to the medical school; this celebrated case helped lead to the passage of the Anatomy Act (1831), which specified that the bodies of the poor who died in workhouses or hospitals be made available for research and teaching.

Over the course of the eighteenth century, Giovanni Battista Morgagni’s attention to autopsy indicated the value of revealing pathological conditions. At the end of the century, Marie-François-Xavier Bichat developed his concept of “general anatomy,” which he defined as the study of the constituent tissues of the human body in health and disease. Bichat’s tissue doctrine turned attention from the clinical description of pathological phenomena to physiological specificity and

physical localization. Following Bichat, Karl von Rokitansky in Vienna brought pathological anatomy to its peak and made it an essential part of medical education in the nineteenth century. The cell theory and improvements in the microscope at midcentury led to Rudolf Virchow's emphasis on the cell as the fundamental unit of anatomy and the ultimate seat of disease, a concept he called his "anatomical idea."

The interest in systematics exemplified by Carl Linnaeus in the eighteenth century also led to a new interest in comparative anatomy as morphological similarities came to be viewed as classificatory signposts. At the Jardin des Plantes, Georges-Louis LeClerc, Comte du Buffon and the anatomist Louis-Jean-Marie Daubenton collaborated on the massive *Histoire naturelle des animaux* (1749–1788), which developed an idea of species based on morphological similarities. In the early nineteenth century, Georges Cuvier continued Daubenton's work on comparative anatomy and combined it with the study of fossils and with Bichat's emphasis on the functionality of the parts of the body to develop his classification of animals. His skills in comparative anatomy and knowledge of the internal structures of animals led to a new classificatory scheme that shattered the old notion of a hierarchical chain of being.

Cuvier's *Règne animal* (1817) identified four principal types of animal form based on structural similarities and functional characteristics: the vertebrates, mollusks, articulates, and radiates. Cuvier's concept of form greatly influenced nineteenth-century work in paleontology and comparative anatomy as well as the theory of evolution. Cuvier's detailed work on fossils confirmed that fossil animals were now extinct, which, to him, did not imply a notion of transformism.

His near contemporary, Etienne Geoffroy Saint-Hilaire, recognized homologous structures in organisms that implied the existence of a generalized type and so opened the door to a transformist, or evolutionary, theory. In the 1830s and 1840s, Richard Owen, who had worked exclusively in comparative anatomy, described an archetype of the simplest vertebrate form. Owen accepted Karl Ernst von Baer's view that embryological development followed a branching, rather than a linear, plan and showed that fossils also show a radiating pattern toward individual specialization rather than a linear progression toward the human form. Charles Darwin did little anatomical work himself. He relied on the investigations of Owen and others on homologies in his theory of evolution by natural selection, published in *The Origin of Species* (1859).

The skeleton, whether animal or human, fossil or new, was at the center of anatomical study. The skeleton appeared at both the beginning and the end of anatomical demonstrations, and took pride of place in anatomy collections. The human skeleton symbolized death and the end of all flesh, and the irreducible bedrock of organic form. In the eighteenth century, some illustrations of skeletons were used to emphasize, and even exaggerate, gender differences. In the nineteenth and early twentieth centuries, skeletons, and especially skulls, were used to adumbrate specious racial theories. The French anthropologist Pierre Paul Broca measured thousands of skulls to confirm his view that skull size (and therefore brain size) correlated with intelligence and with race, gender, and criminality.

By the twenty-first century, anatomical determinism had long been discredited. Dissection, though still important in teaching medicine, had lost its value as a method of discovery. Anatomical atlases display the body in detail and virtual

reality computer programs provide three-dimensional views of everything.

Knowledge of the structure of the living body is now gained in many different ways. X rays, discovered at the end of the nineteenth century, were supplemented in the twentieth by ultrasound, the CT scan, magnetic resonance imaging, and the PET scan. Ultrasound employs high-frequency sound waves that form an image on a monitor. The CT (computerized tomography) scan can be one hundred times more sensitive than conventional X rays. It allows a part of the body to be visualized in "slices" in two or three dimensions. Magnetic resonance imagery (MRI) allows visualization of soft tissue by means of magnetic fields and radio waves. Positron emission tomography (PET) shows the entire body at once. A small amount of radioactive glucose is injected into the bloodstream, after which the patient passes through a scanner like that used in CT scans. These new technologies have provided a cornucopia of information about the structure of the human body.

ANITA GUERRINI

ANTHROPOLOGY. While anthropology has existed as an academic discipline only since the beginning of the twentieth century, the perspective it represents has a considerably longer history. Most anthropologists trace its history to the Anglo-French Enlightenment of the eighteenth century and the ensuing period of European global expansion. The Enlightenment is generally acknowledged for its challenge to "time-honored" traditions and for championing reason as the foundation of truth. The Enlightenment relativized customs and beliefs that had been understood as universal. Jean-Jacques Rousseau's essay, *Discourse on the Origin and Bases of the Inequality among Men* (1754), attributes inequality to the development of private property rather than variable natural endowments or the vicissitudes of nature. Despite the criticism of Rousseau's romantic notion of the "Noble Savage," his sympathetic reference to indigenous peoples anticipated anthropology's critical turn 150 years later by emphasizing humanity's diversity and historical character.

The same historical theme is central to Giambattista Vico's *The New Science* (1725). Vico's book has been claimed as ancestral not only to anthropology but the human sciences more generally because it challenged essentialized notions of human nature. Vico argues like Rousseau against an unchanging human nature and for a vision of humanity as historically produced. For Vico, history presented a more suitable means for grasping the human condition than did the emerging natural sciences, a theme that resonates with contemporary anthropology.

The European expansion throughout the eighteenth and nineteenth centuries contributed significantly to the development of anthropology as an academic discipline. The nineteenth century witnessed the reconfigured political and economic landscapes of European and North American nation-states and indigenous cultures worldwide as colonial sources of labor, raw materials, and export commodities. In a manner that betrayed the critical insights of Rousseau, yet in part fulfilled the nature of Enlightenment reason, nineteenth-century colonialism was regarded in moral terms by many Western scholars, colonial administrators, and missionaries as bringing civilization to so-called "savage peoples." A linear and hierarchical mapping of human history consigned indigenous peoples to the dawn of humanity and place Western peoples at the pinnacle of human development.

enced later figures. Lively controversies over his approach still raged around 1600.

Other sixteenth- and seventeenth-century figures expressed doubts about the possibility of alchemical transmutations and cures, and gradually the hermetic influence declined in Europe. Two of the chief heroes of the Scientific Revolution, Robert Boyle and Isaac Newton, were active in alchemical pursuits, which provides a measure of the staying power of these ideas. Through most of the seventeenth century, however, no one distinguished between scientific “chemistry” and “alchemy” (eventually viewed as pseudo-science); both words existed, but each indicated the same set of diverse activities, practical and mystical. Only during the 1680s did the popular chemical textbook of Nicolas Lewey open the first of a series of attacks on alchemy as fraudulent. Early Enlightenment thinkers then banished “alchemy” to the discredited category of occult doctrines while restricting the word “chemistry” to the science we know today.

A. J. ROCKE

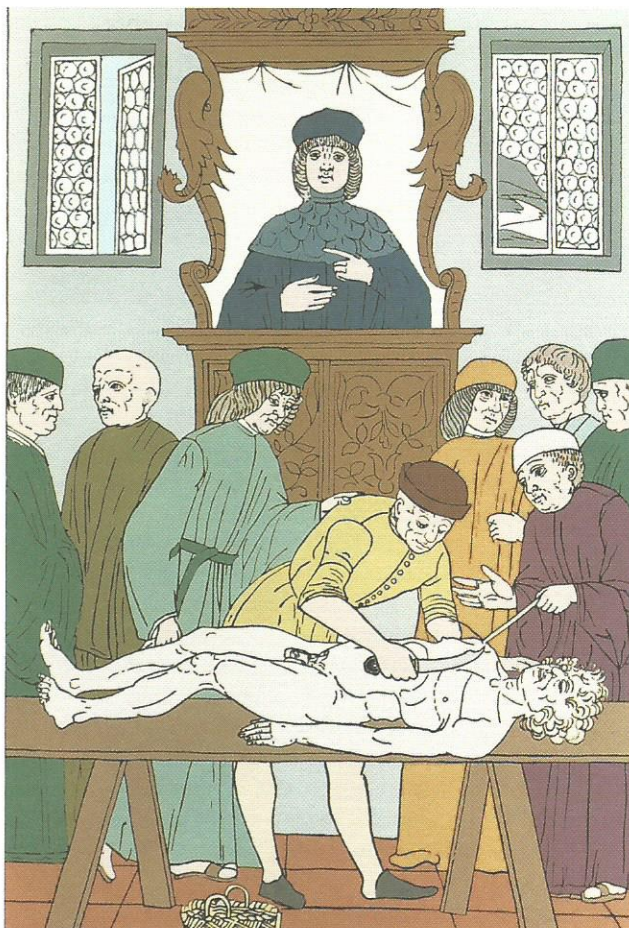
ANATOMY. In modern parlance, anatomy is synonymous with the dissection of a human or animal body. In history, however, the term referred more broadly to a metaphor and a model, a method and a practice. In the early modern period, “anatomy” implied an analysis in the sense of taking something apart—not necessarily a body—to its fundamental components. In the early seventeenth century, Francis Bacon advertised “an anatomy of the world,” and in 1621 Robert Burton published his *Anatomy of Melancholy*.

Through the eighteenth century, anatomy referred both to the act of dissection and to its subject, the human or animal body. In this era, the act referred to both living and dead bodies, although later anatomy came to denote dissection of the dead. In addition, anatomical models, such as wax ones used for teaching purposes, as well as dried and preserved specimens, came under the rubric. Many anatomy cabinets existed to teach students basic structures before they witnessed an anatomy lesson and to reinforce their knowledge afterwards.

Modern anatomy began with the work of Andreas Vesalius and his contemporaries in the sixteenth century. By means of human and animal dissection and animal vivisection, they explored and analyzed the structure of the human body. At almost the same time, however, some anatomists began to find the animal body of interest in itself, and comparative anatomy developed alongside human anatomy.

Anatomy and physiology were not distinct disciplines until the nineteenth century, and early modern anatomists explored both. William Harvey, for example, explained both the form and the function of the human heart and also compared the hearts of different species. Researchers in the seventeenth and eighteenth centuries dissected and vivisected many animals both to explore morphology and, especially, to answer questions about function. Because of the variety of animals they used, much of the work of men such as Marcello Malpighi was broadly comparative. A group of some of the first members of the Paris Academy of Sciences, including Claude Perrault and Joseph-Guichard Duverney, used the resources of the Jardin des Plantes and the menagerie at Versailles to compile their important *Mémoires pour servir à l'histoire naturelle des animaux* (1676), which notes morphological similarities but without an underlying theory of type.

Public anatomy, in which a human cadaver (and usually several live and dead animals) was dissected before an audience, flourished in the seventeenth and eighteenth centu-



Anatomy lecture and dissection from Joannes de Ketham, *Fasciculus medicinae* (1495)

ries. While such exhibitions taught medical students about the form of the human body, they also attracted members of the general public who found the spectacle entertaining and the contemplation of mortality edifying. The decline of public anatomy at the end of the eighteenth century revealed changing sensibilities as well as a recognition that such dissection could no longer reveal anything new.

Municipal authorities usually allowed one or two cadavers of executed criminals per year for public dissection, although the number varied according to local custom. Those who gave multiple courses, or wished to do research, usually resorted to grave robbing. Vesalius bragged about his skill at pilfering corpses. Two centuries later Duverney bribed the grave-digger at the Hotel-Dieu in Paris to provide him with bodies. In England, the so-called Murder Act of 1752 gave the College of Surgeons first right to the bodies of executed criminals, but other researchers and lecturers continued to rely on “resurrection men.” In Edinburgh in the late 1820s, an entrepreneurial pair named Burke and Hare murdered indigent people and sold their bodies to the medical school; this celebrated case helped lead to the passage of the Anatomy Act (1831), which specified that the bodies of the poor who died in workhouses or hospitals be made available for research and teaching.

Over the course of the eighteenth century, Giovanni Battista Morgagni’s attention to autopsy indicated the value of revealing pathological conditions. At the end of the century, Marie-François-Xavier Bichat developed his concept of “general anatomy,” which he defined as the study of the constituent tissues of the human body in health and disease. Bichat’s tissue doctrine turned attention from the clinical description of pathological phenomena to physiological specificity and

physical localization. Following Bichat, Karl von Rokitansky in Vienna brought pathological anatomy to its peak and made it an essential part of medical education in the nineteenth century. The cell theory and improvements in the microscope at midcentury led to Rudolf Virchow's emphasis on the cell as the fundamental unit of anatomy and the ultimate seat of disease, a concept he called his "anatomical idea."

The interest in systematics exemplified by Carl Linnaeus in the eighteenth century also led to a new interest in comparative anatomy as morphological similarities came to be viewed as classificatory signposts. At the Jardin des Plantes, Georges-Louis LeClerc, Comte du Buffon and the anatomist Louis-Jean-Marie Daubenton collaborated on the massive *Histoire naturelle des animaux* (1749–1788), which developed an idea of species based on morphological similarities. In the early nineteenth century, Georges Cuvier continued Daubenton's work on comparative anatomy and combined it with the study of fossils and with Bichat's emphasis on the functionality of the parts of the body to develop his classification of animals. His skills in comparative anatomy and knowledge of the internal structures of animals led to a new classificatory scheme that shattered the old notion of a hierarchical chain of being.

Cuvier's *Règne animal* (1817) identified four principal types of animal form based on structural similarities and functional characteristics: the vertebrates, mollusks, articulates, and radiates. Cuvier's concept of form greatly influenced nineteenth-century work in paleontology and comparative anatomy as well as the theory of evolution. Cuvier's detailed work on fossils confirmed that fossil animals were now extinct, which, to him, did not imply a notion of transformism.

His near contemporary, Etienne Geoffroy Saint-Hilaire, recognized homologous structures in organisms that implied the existence of a generalized type and so opened the door to a transformist, or evolutionary, theory. In the 1830s and 1840s, Richard Owen, who had worked exclusively in comparative anatomy, described an archetype of the simplest vertebrate form. Owen accepted Karl Ernst von Baer's view that embryological development followed a branching, rather than a linear, plan and showed that fossils also show a radiating pattern toward individual specialization rather than a linear progression toward the human form. Charles Darwin did little anatomical work himself. He relied on the investigations of Owen and others on homologies in his theory of evolution by natural selection, published in *The Origin of Species* (1859).

The skeleton, whether animal or human, fossil or new, was at the center of anatomical study. The skeleton appeared at both the beginning and the end of anatomical demonstrations, and took pride of place in anatomy collections. The human skeleton symbolized death and the end of all flesh, and the irreducible bedrock of organic form. In the eighteenth century, some illustrations of skeletons were used to emphasize, and even exaggerate, gender differences. In the nineteenth and early twentieth centuries, skeletons, and especially skulls, were used to adumbrate specious racial theories. The French anthropologist Pierre Paul Broca measured thousands of skulls to confirm his view that skull size (and therefore brain size) correlated with intelligence and with race, gender, and criminality.

By the twenty-first century, anatomical determinism had long been discredited. Dissection, though still important in teaching medicine, had lost its value as a method of discovery. Anatomical atlases display the body in detail and virtual

reality computer programs provide three-dimensional views of everything.

Knowledge of the structure of the living body is now gained in many different ways. X rays, discovered at the end of the nineteenth century, were supplemented in the twentieth by ultrasound, the CT scan, magnetic resonance imaging, and the PET scan. Ultrasound employs high-frequency sound waves that form an image on a monitor. The CT (computerized tomography) scan can be one hundred times more sensitive than conventional X rays. It allows a part of the body to be visualized in "slices" in two or three dimensions. Magnetic resonance imagery (MRI) allows visualization of soft tissue by means of magnetic fields and radio waves. Positron emission tomography (PET) shows the entire body at once. A small amount of radioactive glucose is injected into the bloodstream, after which the patient passes through a scanner like that used in CT scans. These new technologies have provided a cornucopia of information about the structure of the human body.

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The nineteenth century saw a critical tension between intellectual commitment to social evolution and opposing discourses that embraced evolution while supporting an alternative vision of indigenous peoples. The encounter with indigenous peoples could be an occasion for the celebration of difference and for exploring alternative possibilities for the human condition. The works of Lewis Henry Morgan, often regarded in anthropology as the founder of modern kinship studies, illustrate the point. In *League of the Iroquois* (1851) and *Ancient Society* (1877), Morgan showed the wide variability of kinship structures in relation to property and changing forms of human community. His work caught the attention of Karl Marx, who used it to show that many of the characteristics nineteenth-century scholars attributed to human nature were in fact particular to the history of capitalism. Morgan and Marx can be claimed as anthropological ancestors because they appreciated the unique historical nature of indigenous societies as a challenge to regnant ideas of unilineal development and progress that ultimately dismissed the humanity of indigenous peoples.

Anthropology Enters the Academy

The founding of American academic anthropology can be attributed to the German immigrant Franz Boas, while English and French anthropology owes much to the intellectual traditions established by Herbert Spencer and Emile Durkheim. Named Professor of Anthropology at Columbia University in 1896, Boas gained the institutional support that enabled him to launch Columbia as the outstanding American center for anthropological research and training of the early twentieth century.

Boas advocated local histories and strongly supported the American four-field approach, integrating cultural anthropology, archaeology, linguistics, and biological anthropology. He criticized nineteenth-century unilineal evolution and argued that ethnographic materials, practices, and culture should be understood from the context of their development. Boas brought linguistic, cultural, archaeological, and biological evidence to bear in studying the historical origins of cultural phenomena. However, his promotion of the American four-field approach came from his ethnographic research on America's indigenous population and his critique of the racist policies espoused by the American Immigration and Naturalization Service at Ellis Island. His numerous students—Margaret Mead, Ruth Benedict, and others—left a lasting mark on American anthropology.

One would expect Edward Tylor's classic *Primitive Culture* (1871), rather than Herbert Spencer's *The Principles of Sociology* (1885) and Emile Durkheim's *Rules of the Sociological Method* (1895), to be the pervasive intellectual influence on British social anthropology given the enduring nature of Tylor's cultural concept of the "complex whole." However, Tylor embraced evolutionism and failed to establish a tradition of field work as the foundation of anthropological practice. Spencer favored an organic model of human society, while Durkheim introduced the notion of the "social fact" to explain the relation between the human individual and the determining cultural influences of groups or communities as the basic unit of social analysis. Spencer and Durkheim served as principal influences on British functionalism and structural-functionalism more generally, which rested on the pervasive idea that social beliefs and practices reinforce the identity and continuity of the social whole.

Bronisław Malinowski was primarily responsible for establishing rigorous field research as the hallmark of socio-

cultural anthropology. In contrast to much of late nineteenth- and early twentieth-century anthropology, in which fieldwork was not considered suitable for "gentlemen," Malinowski argued for immersion in the social round of indigenous societies over a sustained period of time. He also emphasized in *Argonauts of the Western Pacific* (1922) the importance of learning indigenous languages, of being able to "think in their symbols." He rejected evolutionary models and was skeptical toward historical approaches he considered too dependent on oral accounts. Malinowski argued for an organic vision of society as consisting of interdependent parts and emphasized individuals and the capacity of culture to satisfy their biological, psychological, and social needs.

Alfred Reginald Radcliffe-Brown's structural-functionalism was the primary competitor to Malinowskian functionalism. Radcliffe-Brown made his reputation through field research in the Andaman Islands and Australia, and, unlike Malinowski, placed a theoretical emphasis on social structure rather than the individual. For Radcliffe-Brown and Durkheim, individuals come and go while social structures endure. However, both Malinowski and Radcliffe-Brown conceived of societies as integrated wholes, and conflict as essentially dysfunctional. They and their students worked during the period of English colonial rule. While the connection between English social anthropology and colonialism was indirect, Malinowski and Radcliffe-Brown's rejection of history and de-emphasis of human agency except as a function of needs and structures precluded a critical understanding of the social, political, and economic circumstances that prefigured the anthropology of their times.

There is little doubt that Claude Lévi-Strauss remains the predominant figure in French anthropology. His work was heavily indebted to Durkheim, especially his *Elementary Structures of Kinship* (1949), as well as to the formalism of the Prague school of linguistics. Lévi-Strauss's most famous book, *Tristes Tropiques*, reported on his sole fieldwork experience.



Margaret Meade (1901–1978), American anthropologist widely known for her best seller, *Coming of Age in Samoa* (1928)

rience, in the Amazon. This book is celebrated for its elegant prose and the questions it raises with respect to overcoming the cultural distance that separates the ethnographer from the indigenous “other.” However, unlike Malinowski, Lévi-Strauss committed his scholarly career to anthropology from a distance through the formal analysis of myths worldwide. He argued that in spite of the variability of narratives or stories, myths should be understood as permutations of invariable human themes. The structural method, the internal mechanics of the myth’s primary oppositions, enabled Lévi-Strauss to transform the surface semantics of a myth to its underlying universal logic.

Structuralism and structural-functionalism continued to be influential right through the colonial era until it subsided in the wake of the critical anthropology of the 1970s. However, with the exception of sociology and political science, the influence of critical anthropology tended to be more pronounced in England and continental Europe than in the United States. Not all versions of structuralism reproduced the original models established by Malinowski, Radcliffe-Brown, and Lévi-Strauss. Edmund Leach introduced a more dynamic version of structuralism than his English predecessors, exhibiting a sensitivity to history and human agency in *Political Systems of Highland Burma* (1954). Although reproducing the functionalism of his mentor Malinowski with an ecological tone, E. E. Evans-Pritchard, like Leach, was more attuned to the importance of history to anthropology. Well versed in the hermeneutic philosophy of Wilhelm Dilthey, Evans-Pritchard identified anthropology with the human rather than natural sciences. The symbolic structuralism of Victor Turner’s analysis of rituals and Mary Douglas’s use of structure and anti-structure to articulate boundaries and matter out of place also influenced structuralism and functionalism. However, they lacked the deeper reflective and historical perspective necessary to grasp the intellectual contiguity between static theoretical models and the politics of European colonialism.

Mead and Benedict followed up Boas’s work on the relation between culture and personality. Mead’s books became known worldwide and posed a considerable challenge to dominant ideas of sex and gender. Edward Sapir advanced Boas’s initiatives on language by arguing for the close association between language and worldview, a perspective now known as “linguistic relativity.” Sapir evaluated the potentials that human cultures offered individuals in his important essay “Culture, Genuine and Spurious” (1924), which engaged Alfred Kroeber’s notion of culture as “superorganic,” suspended above the fray of daily practice. Sapir taught that cultures were genuine only if they enhanced the potentials of individuals, and so spoke positively of indigenous societies.

In both the specific traditions of French and British sociocultural anthropology and the American four-field approach, the culture concept served as the common bridge and point of contest among disparate theoretical traditions and practices. Even adamant defenders of the primacy of structure had to concede something to the “cultural other.” Throughout the 1930s and 1940s there was wide agreement on fieldwork as central to the identity of anthropology, but “culture” eluded all efforts at operationalization. Perhaps out of resignation, Tylor’s view of culture as the “complex whole” served as the minimalist position.

In the 1950s, American anthropology took a dramatic materialist turn through the theoretical contributions of Leslie White and Julian H. Steward. Following the influence of Karl Marx, both White and Steward argued against

explaining culture in cultural terms. White embraced in *Evolution of Culture* (1959) a comprehensive theory of unilineal social evolution that had long been criticized and abandoned by the Boasian tradition. According to White, the capacity to harness energy was the primary force in societies’ progress from one stage of technological complexity to another. On the other hand, Steward sought, in his *Theory of Culture Change* (1955), to distance himself from the untenable Eurocentric implications of nineteenth-century social evolution. Like Boas, Steward was sensitive to the historically particular in arguing that cultures could evolve in distinct patterns, depending on diverse environmental circumstances. He called this “multilineal evolution.” Although Steward emphasized material processes as central to evolution, he did not dismiss the importance of culture. Rather, culture was central to his theoretical framework through the “culture core,” the cultural activities most directly related to subsistence.

Contemporary Directions

The end of European colonialism during the 1960s and the political initiatives taken by newly independent states rendered problematic such static theories as structuralism and structural-functionalism, which dismissed history and eclipsed human agency. Anthropologists pursued numerous new directions. Marxist anthropology developed in the United States and France in the 1960s followed by the very important and influential appeal of Dell Hymes, who sought to refigure anthropology along critical lines in his edited *Reinventing Anthropology* (1969). In the United States, three of Steward’s students—Stanley Diamond, Sidney Mintz, and Eric Wolf—elaborated Marxist anthropology. Diamond wrote romantically, as had Rousseau and Marx, about alternative potentials of human freedom based upon the reputed equality of indigenous societies. Mintz and Wolf advanced understanding of peasant societies and capitalist accumulation through their work on the Caribbean and Mexico, respectively. Hymes’s book of 1969, which included contributions from Diamond, Wolf, Scholte, and others less directly related to the Marxist tradition, called for the political reformulation of anthropology in a manner that acknowledged the close connections between anthropology and colonialism. According to the “reinventing” group, the practice of anthropology should not be divorced from political practice and should be sensitive to the social, political, and historical circumstances that concretely locate anthropology as a discipline.

French anthropology had its own version of Marxism represented in the works of Maurice Godelier and Claude Meillassoux. Godelier and Meillassoux wrote prolifically on the application of mode of production analysis to indigenous societies. They wrote, however, from a largely structuralist perspective that tended to grasp culture as shaped by the forces and relations of production. Godelier invoked the traditional Marxist categories associated with the mode of production and criticized Meillassoux for inventing a new mode of production for every variant in an indigenous social order. Godelier has recently moved away from the strict base-and-superstructure model of Marxism and has been a major figure in establishing a tradition of French anthropology distinct from that of Lévi-Strauss. Recent French anthropologists like Françoise Zonabend have clearly broken from both the colonial past and Lévi-Strauss by focusing on ethnographically detailed and historical accounts of rural France.

White’s and Steward’s materialism also influenced the development of American cultural ecology. Marvin Har-

ris is perhaps the best known of the cultural materialists. Although hostile to American Marxist and critical anthropology for embracing dialectics and disavowing science, Harris borrowed such concepts as “mode of production,” “etic behavioral mode of production and reproduction,” and “emic superstructure” strangely reminiscent of Marx. Emics has traditionally referred to the informant’s perspective, while etics entails the studied conclusions of the researcher. However, Harris regards culture as derivative of a techno-environmental determinism, a perspective quite remote from Marx and Marxist anthropology. The cultural ecology of Roy Rappaport presents a more subtle and complex rendering of human culture. In *Pigs for the Ancestors* (1967) Rappaport shows how the horticultural Maring of New Guinea use ritual and symbols to mediate the ecology of their gardens, thus avoiding the reductive tendencies associated with ecological castings of culture and daily practices.

Clifford Geertz’s *The Interpretation of Culture* (1973), a book whose concept of “thick description” has influenced scholars from history to literary criticism, redefined the concept of culture as lived symbolic beliefs and practices having public meanings. Geertz argued that anthropology was not a science in search of laws but a hermeneutic one in search of meaning, a remark that essentially identifies one of the primary tensions in contemporary anthropology.

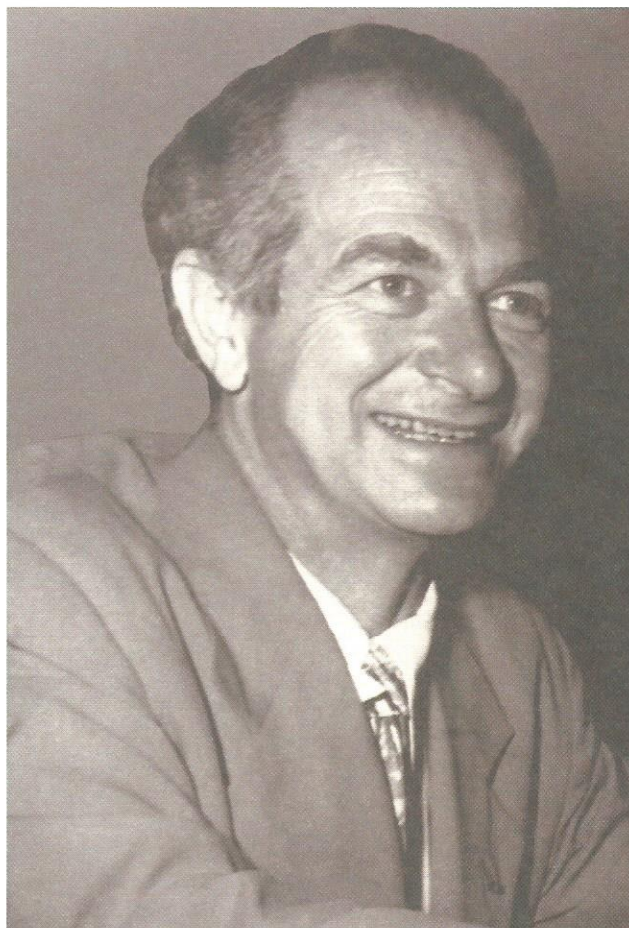
Other new directions also seek to bridge political economy and cultural theory. Recently, Marshall Sahlins has sought to reinvigorate structuralism by developing a dynamic, if not dialectical, relationship between structure and agency. George Marcus and James Clifford’s *Writing Culture* (1986) contributed importantly to serious discussion of the rhetorical and political dimensions of ethnographic writing, a concern foreshadowed earlier in the writings of historian Hayden White. Marcus, Clifford, Fischer, and especially Tyler have come to be associated with anthropology’s post-modern turn through challenging meta-narratives and privileging ethnography as local pastiche.

On another front, contributors to *Recapturing Anthropology* (1991), edited by Richard Fox, and *Anthropological Locations* (1997), edited by Akhil Gupta and James Ferguson, have discussed the reinventing of anthropology to address the problems that ensue from globalization and cultural diaspora. Authors in both volumes argue against the antiquated notion of a circumscribed field site and for what George Marcus calls multisited field research. Moreover, like John and Jean Comaroff and Johannes Fabian, Lila Abu-Lughod argues against univocal views of culture and for culture as contested practice.

Anthropology continues to challenge its own assumptions and to seek to respond to global dislocations and inequalities. Within American anthropology, some academic departments like Stanford’s and Duke’s have been torn apart by struggles over science and critical practice, while others seek new ways to bridge the subdisciplines. It seems clear that anthropology on a global basis will continue to be relevant to the challenges that face humanity because it is one of the few disciplines that through its critical practice embraces both diversity and interdisciplinary modes of knowing.

ROBERT C. ULIN

ANTINUCLEAR MOVEMENT. From their inception nuclear weapons were controversial, and this ambivalence extended to their civilian counterpart, nuclear reactors, because of the dangers associated with them.



Linus Pauling (1901–94), winner of the Nobel Prize for chemistry in 1954 for work on the chemical bond and of the Nobel Prize for Peace in 1962

Opposition to Nuclear Weapons

The United States used nuclear weapons against Hiroshima and Nagasaki in August 1945 to hasten the end of World War II. Since then, despite calls for their use in the Korean and Vietnamese conflicts and concerns about their employment during the Cuban missile crisis, no nuclear weapon has been fired in anger.

Although the victors of World War II regarded the atomic bomb as the “winning weapon” and expected it to keep the peace, many people considered it an immoral weapon. The Soviet Union’s explosion of its first device in 1949 made clear that a nuclear war would be catastrophic for its participants.

The first antinuclear protesters were the Manhattan Project scientists themselves. The wartime Franck Report (named after its principal author, the emigré Nobel Prize-winning physicist James Franck) unsuccessfully urged the U.S. government to issue a warning before dropping a bomb on a city. After the war’s end, many scientists joined journalists, clergy, and other citizens in advocating domestic legislation to ensure civilian control of nuclear research and development, and strong international control of weapons through the newly formed United Nations. The Federation of American Scientists (FAS) led these efforts. A best-selling anthology of articles by leading scientists, *One World or None* (1946), helped mobilize public opinion.

During the mid-1950s, testing of newly developed hydrogen bombs revealed the danger of radioactive fallout circulating worldwide. A petition to ban testing, drawn up by the Nobel Prize-winning chemist Linus Pauling and signed by thousands of scientists, raised the level of international con-



The area in the Yucca Mountains on the boundary of the Nevada Test Site was proposed as a repository for high-level nuclear waste.

cern. The National Committee for a Sane Nuclear Policy (SANE) and the Campaign for Nuclear Disarmament (CND) sprang up in the United States and Britain, respectively. These and “ban the bomb” organizations in other countries were often slandered as procommunist. They obtained a following by appealing to the emotions, which allowed opponents to charge, with some accuracy, that they knew little about weapons and strategy. The Limited Test Ban Treaty of 1963, which permitted testing only underground and so removed fallout as an issue, deprived the antinuclear movement of much of its emotional steam. In the 1970s, however, a revitalized FAS, together with the Union of Concerned Scientists, the Council for a Livable World, the Center for Defense Information, Physicians for Social Responsibility, and the American Physical Society, developed arguments that appealed to the intellect as well as the emotions. Composed in large part of scientists, physicians, and retired military officers, their expertise and patriotism could not be impugned.

Organized religion, surprisingly, was not an early and persistent critic of weapons of mass destruction; many churches supported the anticommunist sentiments of the period. During the 1980s, however, several panels of Catholic and Protestant bishops issued reports questioning the morality of nuclear deterrence. Filmmakers created visual images of the horrors of nuclear warfare in *The War Game*, *Threads*, *On the Beach*, and *The Day After*, and exposed the danger and absurdity of war initiated by a maniac (*Dr. Strangelove*) or by technological failure (*Fail Safe*).

The United States did not have a monopoly on antinuclear agitation. The Japanese people keep the memory of the bombings of 1945 alive in annual ceremonies in the Hiroshima Peace Park, which has a museum of artifacts and pictures. The government of India, acting as a leader of developing countries, criticized the superpowers' arsenals until it developed its own nuclear weapons. In the Soviet Union, physicist Andrei Sakharov first designed hydrogen bombs and then campaigned vigorously against their use. The Soviet government supported International Physicians for the Prevention

of Nuclear War, a Nobel Peace Prize-winning organization (1985) founded by a Russian and an American. The Pugwash movement, a decades-long series of conferences by scientists from many countries, also received the Nobel Peace Prize (1995). The Green party and other organizations in Germany organized massive marches in the early 1980s to protest the introduction of intermediate-range ballistic missiles with atomic warheads in Europe. Australians and New Zealanders objected to tests by France in the South Pacific as late as the 1990s.

A number of international treaties have created nuclear weapon-free zones in Antarctica (1959), Latin America (1967), the South Pacific (1985), Southeast Asia (1995), and Africa (1996). These accords are more than mere gestures of compliance, but less than enforceable laws. Seeking an outright legal ban on nuclear weapons, a number of nongovernmental organizations requested a ruling from the World Court. The court issued an advisory opinion in 1996 stating that “the threat or use of nuclear weapons would generally be contrary to the rules of international law.”

Opposition to Reactors and Radioactive Waste

The United States drew a sharp separation between civilian reactors primarily producing electricity and military reactors primarily growing plutonium. American utilities that owned reactors did not want the albatross of militarism hung around their necks. In other countries, such as Great Britain, reactors served dual purposes. Since all reactors produce plutonium that could become fuel for breeder reactors as well as an explosive, many people feared that terrorists might hijack some of the metal while it was in transit.

During the 1960s and early 1970s, American utilities ordered the building of more than one hundred reactors. Grassroots opposition coalesced around fear of lethal doses of radioactivity released in a meltdown of the core (the theme of the popular film *The China Syndrome*), but other potential problems added to popular concerns: Lesser accidents might release dangerous levels of radioactivity beyond the

site perimeter; plans for plants close to urban areas increased anxiety; water from the reactors' cooling system dumped in rivers, lakes, and oceans threatened fish and other animals; and the likely targeting of reactors in a nuclear war made them undesirable neighbors.

By protesting reactor plans at every stage, the opposition (often local citizen groups) slowed the building process so much that the utilities incurred enormous interest charges on the money they borrowed for construction. This often made the proposed reactor uncompetitive with fossil-fuel. By the early 1970s, some utilities had canceled their plans for reactors (not only because of the high costs but also owing to overestimates of the nation's electrical needs). A safety report by the U.S. Nuclear Regulatory Commission in 1975, which minimized the dangers of reactors, was widely criticized. Since 1974, not a single utility in the United States has ordered a reactor, although American manufacturers continue to construct them for other nations. About 100 aging reactors provided around 20 percent of domestic electricity in the United States in 2000. The corresponding numbers were considerably higher in France and Japan.

The U.S. Atomic Energy Commission (AEC) began to promote construction of civilian reactors in the 1950s but did not give sufficient attention to waste disposal. High-level radioactive wastes were planned to be stored "permanently" in abandoned salt mines in Kansas in the 1970s. When Kansas state geologists showed the presence of drill shafts that would allow the entrance of rainwater, the AEC abandoned the site.

No state then volunteered to accept a high-level waste repository. Spent fuel rods accumulated in the already crowded cooling ponds at each reactor location. In the 1980s, the U.S. Congress forced development of the Yucca Mountain site in Nevada, but even after the expenditure of more than four billion dollars by the end of the twentieth century, all the technical problems of containing radioactivity there for ten thousand years had not been solved.

The states of Nevada, Washington, and South Carolina accepted low-level radioactive wastes from universities, hospitals, and industry until the accident at Three Mile Island in Pennsylvania (1979) and the catastrophe at Chernobyl, Ukraine (1986). So-called NIMBY ("not in my backyard") opposition, often based on the fear that radioactivity would reach urban water supplies, then stifled progress in waste disposal. Having brought the nuclear reactor industry to a standstill in the 1970s, the antinuclear movement joined with state and local officials and increasingly sophisticated antinuclear and environmental organizations, such as the Sierra Club, Natural Resources Defense Council, and Union of Concerned Scientists, to challenge proposals for siting storage facilities.

Elsewhere, opposition to reactors has also been effective. In 2000 Germany decided to close all its nuclear power reactors within twenty years. The Green party, one of the few environmental groups to have members elected to a national parliament, turned its once-ridiculed position into national policy. Civilian antinuclear activities have also succeeded in opposing nuclear-powered merchant ships, which many ports now ban. Fears of radioactive contamination faced the American *Savannah* (launched in 1962), the German *Otto Hahn* (1964), the Japanese *Mutsu* (1972), and the Soviet *Sermorput* (1989). Like reactors used to produce electricity, propulsion reactors changed from a once-promising technology into expensive, controversial, and feared objects. It would be premature to bury nuclear power, however. As

other sources of energy fall behind the world's demand and air pollution from fossil-fuel plants reaches unacceptable levels, there may be no alternative but self-denial to the nuclear reactor.

LAWRENCE BADASH

ARISTOTELIANISM became the philosophy of the newly formed universities of Oxford and Paris and other higher schools during the thirteenth century. The Council of Trent (1545–1563) declared Thomistic Aristotelianism to be the official doctrine of the Roman Catholic church. Aristotelianism retained its cultural, theological, and intellectual dominance even in Protestant countries well into the seventeenth century although Aristotelian natural philosophy met with telling criticism during the Scientific Revolution. Elements of Aristotle's philosophy continued to influence the development of science well into the nineteenth century.

In 1586 the Jesuits introduced the "*Ratio studiorum*" (revised in 1599 and 1616) that established the standard texts used for teaching Aristotelian philosophy at their colleges, including La Flèche (where René Descartes was educated) and their central teaching establishment, the Collegio Romano. Many Christian non-Jesuitical institutions adopted the *Ratio* in one form or another. In general, the texts favored by the Jesuits described a physical world consisting of four elements (earth, air, water, and fire) that in varying combinations composed all earthly bodies. The texts portrayed a geocentric universe and maintained that the Copernican heliocentric theory of 1543 was at best a mathematical tool for calculating the positions of celestial bodies. Traditionalists like the Jesuit cardinal Robert Bellarmine of the Collegio Romano and the authors of the commentaries on Aristotle's *Libri naturales* issued by the University of Coimbra around 1600 showed how to reconcile new observations with Aristotelian theory. Philosophers like Galileo's friend and colleague at the University of Padua, Cesare Cremonini, defended these accommodations because they preserved the systematic explanations of Aristotle against Galileo's piecemeal, unsystematic approach. The close relation between Catholic dogma and Aristotelian doctrine also encouraged continuing with the older philosophy.

Increasingly, the alterations produced by individuals in an attempt to keep Aristotelianism coherent in the face of new observations in astronomy and elsewhere resulted in the erosion of agreement on specific philosophical details. Despite these variations, however, Aristotelianism continued to offer a framework for constructing plausible explanatory systems. The framework considered natural bodies in terms of matter, privation, and form, which gave individual portions of matter the qualities that characterize particular bodies. Four different causes elucidated the generation, construction, or alteration of a body: the material cause out of which the change comes; the formal cause that provides the specifying or defining factor; the agent or efficient cause that initiates the change; and the final cause that provides the purpose (*telos*) for which a thing came into existence.

The mechanical philosophy of the seventeenth century subverted the framework. In his *Discourse on Method* (1637), Descartes rejected the notion of final causality and the theory of four qualitatively different elements in favor of one undifferentiated matter. In place of the Aristotelian qualitative approach to explanation, Descartes defended, though he seldom practiced, a quantitative and mathematical method that referred the manifest properties of bodies to the

effects of bits of matter in motion. Despite these disagreements of principle, Descartes wrote in a systematic, deductive style agreeable to the Aristotelians, and he presented his works to his former teachers, the Jesuits at La Flèche and Paris, explicitly asking for, although never receiving, their approbation.

In England, Francis Bacon directed his criticism of the Aristotelian framework primarily against its use of syllogistic reasoning to construct elaborate theoretical systems. In *The New Organon* (1620), he argued that the syllogism should serve only as a method of demonstration. It could not be used for the discovery of new knowledge or for the production of new works. In place of the syllogism, Bacon advocated an inductive method based upon the careful compilation and analysis of observational and experimental data. Bacon also rejected the notion of the four elements. He retained the notion of forms, but he described them in a mechanical fashion as the laws that governed the motions of bodies. Although Descartes and Bacon both rejected the Aristotelian conception of final causality, not all mechanical philosophers did. Robert Boyle, who brought together the Baconian and mechanical programs in the next generation, maintained that teleological inferences, such as those used by William Harvey in elucidating his discoveries concerning the circulation of the blood (1628), were a necessary adjunct to mechanical hypotheses in biological investigations.

Parts of the works of Galileo, Descartes, Bacon, and Boyle were placed on the church's *Index of Prohibited Books* and opposed by the Jesuits. Aristotelians such as Antoine

Goudin, Jean-Marie-Constant Duhamel, and Jacques Grandamy continued to write well into the eighteenth century, often setting the agenda and parameters for philosophical debate. By the nineteenth century Aristotelianism was no longer viable as a natural philosophy. Even so, remnants of it continued to be influential, primarily in the study of living matter. Thomas Aquinas had used Aristotle's natural philosophy to construct a teleological proof for the existence of God. In the seventeenth century John Ray argued for the necessity of a designer God based upon considerations drawn from observations of the complexity and organization exhibited in living systems. Although belief in the purposefulness of nature opposed strict mechanistic laws, at the end of the seventeenth century Richard Bentley constructed teleological arguments based upon considerations drawn from Newtonian mechanics. William Paley would continue to popularize this type of argument in his *Natural theology* (1802). By the mid-nineteenth century, however, defenders of Darwinian evolution rejected the Aristotelian idea of purposes in nature, and the stage was once again set for a fierce battle between religion and science.

ROSE-MARY SARGENT

ARTIFICIAL INTELLIGENCE. The first machines simply augmented human or animal muscle power, but later pre-industrial inventors introduced devices that also augmented or replaced the human intellect: for example, windmills with sails that adjusted for the intensity of the wind and float valves that maintained water in a tank at a desired level. These devices used the technique of feedback, whereby information about a machine's status or behavior—say the height of water in a tank—is fed back to the input stages—the valve supplying water to the tank. By the nineteenth century, the development of information-processing machines reached a sufficient level to generate speculation about the similarities between self-regulating mechanisms and human thought processes. The most famous publication on this theme was Mary Shelley's *Frankenstein* (1818), whose main character (Frankenstein's creation) has entered popular consciousness not as a person but as anything that becomes dangerous to its creator. Further philosophical speculation on this topic followed. In 1889, Mark Twain discussed the intelligence of the Paige typesetting machine, whose mechanical complexity outdistanced its day and almost bankrupted its inventor. Specifically, Twain believed that the Paige machine's ability to right-justify type automatically—something that he knew required human skill—was an obvious indication of mechanical intelligence.

The invention of the digital computer in the mid-twentieth century once again raised these philosophical questions. In 1948, Norbert Wiener, a mathematician at Massachusetts Institute of Technology, coined the term "cybernetics" in a book that discussed not only the mathematical nature but also the philosophical implications of some machines. These machines could regulate themselves to adjust to changes in their physical environment, select alternative courses of action based on the results of previous actions, and remember what actions they had taken in the past—and their consequences. In short, they could learn from experience, adapt to new conditions, and interact with their human creators.

In England in 1951 Alan Turing published a paper that described a form of parlor game in which players guessed whether they were communicating (through a teletype or similar impersonal device) with a person or a machine (a computer). If players could not distinguish between human



A fanciful portrait from 1702 of the Greek philosopher Aristotle (384–322 B.C.)

and computer, Turing argued, they would have to concede that the computer is “intelligent.” The Turing Test for machine “intelligence,” a concise, simple, and witty definition of a seemingly intractable conundrum, remains valid. No machine has ever passed the test, although in some restricted domains computers come close.

Similar interests in machine intelligence arose in the United States. At a seminal conference at Dartmouth College in 1956, John McCarthy coined the term “artificial intelligence” (later shortened to AI) to describe ways of making computers act “intelligently.” (Some accounts of the Dartmouth conference mention that the group considered Wiener’s term “cybernetics,” but rejected it so as to avoid introducing a philosophical dimension to their work. Wiener’s term resurfaced in the 1990s as “cyberspace,” meaning a world existing entirely inside networks of computers.) One of McCarthy’s colleagues, Marvin Minsky, defined AI as “the science of making machines do things that would require intelligence if done by men.” The term has been criticized for being vague and imprecise; yet it has persisted, perhaps because it captures the imprecision and frustration encountered by humans when they try to understand in an objective way intelligent behavior—what most humans, even children, do effortlessly.

McCarthy developed the programming language LISP (List Processing), which simplified the writing of programs that handled symbolic and logical problems as opposed to numerical problems, which other programming languages were designed to solve. For years LISP remained the preferred language for AI researchers. For nearly all of AI’s history, research consisted mainly of writing programs in LISP for ordinary, general-purpose electronic computers. A famous example, ELIZA, mimicked a question-and-answer session between psychoanalyst and patient. AI has focused primarily on computer programming, using text almost exclusively as input and output in keeping with the Turing Test for intelligence. AI has little connection with robotics, the art of building machines that replicate activities carried out by intelligent creatures. Occasionally AI researchers have attempted to couple their programs to microphones, loudspeakers, cameras, electric motors, and so forth, but these projects were exceptions. AI researchers argue that understanding basic cognition gives them enough to do. Also, the U.S. Defense Department’s Advanced Research Projects Agency (ARPA), which provided most of the funding for AI research, supported the restricted definition of AI’s domain. Since about 1985, AI and robotics have moved much closer together, in part because ARPA’s support for AI was drastically cut in that year and because computers, cameras, sensors, motors, and so forth have become much smaller and more capable of putting AI ideas into practice.

Attempts to get computers to perform intelligent tasks have led to new insights into human psychology, and AI has given new life to philosophy as well. But AI research has not led to easier methods of programming computers or to techniques of writing computer programs without errors—both very desirable goals for which the marketplace would pay well. Nor does it have a cupboardful of exemplary programs. As soon as AI perfects a program that can do what was once considered a task requiring human intelligence, computer scientists no longer see it as important and it is demoted from its classification as AI. In the early 1950s computer scientists thought that getting a computer to play a good game of chess would penetrate to the basis of human intelligence. By 1996 a chess program had defeated the human World Champion, and



US mathematician Norbert Wiener (1894–1964), founder of cybernetics, photographed in 1962

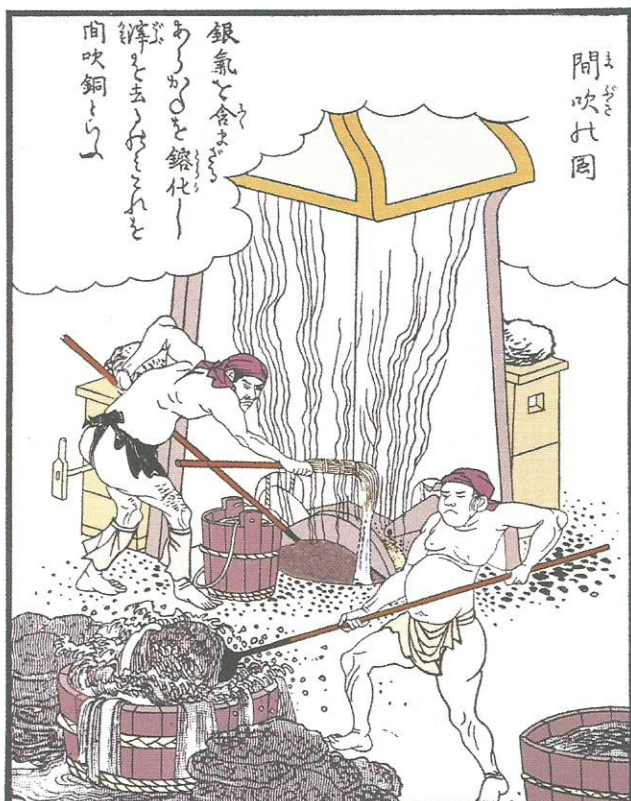
pocket chess computers that played a respectable game were selling for \$30. Consequently, AI researchers no longer consider chess such an important topic. Pocket computers that recognize handwriting have captured another frontier of AI research.

The branch of AI called expert systems has had some commercial success. Expert systems consist of large structured pools of data on a specific topic—say, medical diagnosis—plus a set of rules acquired by interviewing specialists in the field—in this case, skilled physicians. The resultant system performs as well as and in some cases better than humans. The most famous fictional computer, HAL, of the 1968 Stanley Kubrick film *2001: A Space Odyssey*, could diagnose and suggest repairs for the spacecraft on which it traveled. HAL’s voice recognition—really voice understanding—has not been approached in reality, although some progress has occurred with limited vocabularies. And HAL’s emotional breakdown suggests a mentality that no computer today comes close to achieving. Researchers have reached no agreement on how to program so sensitive a computer or whether such a program is even possible.

Artificial intelligence continues to defy easy definition. It has not produced any dramatic breakthroughs—something that people seem to demand elsewhere in computing—but over the years it has made genuine progress. Its principal contribution to society may lie more in telling human beings about themselves than in providing us with the more prosaic benefits of computer technology.

PAUL E. CERUZZI

ASIA. As the world’s largest and most culturally diverse region, modern Asia displays an exceedingly wide range of scientific achievements and institutions, with historical patterns to match. Japan lies at one end of the spectrum, Bhutan or Laos at the other. Two in the middle, India and China, are among the world’s oldest recorded civilizations; both participated in modern science during the twentieth century, and to some extent before. And each can boast of important scientific achievements from the pre-modern era. The fourteen Nobel Prizes in science awarded to



Copper production in ancient Japan. From Brian Hickman, *Japanese Crafts* (1978)

investigators from Asia constitute an imperfect indicator of the region's standing in modern science; and it is telling that only half of the prizes went for work done in Asian countries. This record serves as a stark reminder of Asia's strengths in, and contributions to, modern science, on the one hand, and of the weaknesses and continuing difficulties that confront science in the region, on the other.

Origins and Early Growth

Modern science in Asia traces its origins to the arrival of European scientists interested in the region's flora, fauna, minerals, topography, and so on. India, China, the Philippines, and Japan felt the European Scientific Revolution through the activities of Jesuit missionaries in the late sixteenth and early seventeenth centuries, although the Philippines had a European style college by the early seventeenth century. Spain, as the dominant power in the country, long remained marginal to the scientific enterprise. The sustained development of modern science in Asia actually began with the arrival of British scientists in India shortly before 1800. Other European investigators followed, to China, Southeast Asia, Japan, and elsewhere; but developments in India proceeded more rapidly because of the subcontinent's continuing, ever-more intimate association with Britain. British scientists carried out astronomical studies in Bengal and a Trigonometric Survey throughout the whole of India (including today's Pakistan and Bangladesh) beginning in 1800. These and other early investigations simultaneously satisfied curiosity and promoted British commercial and political interests in the region. Direct Crown Rule, however, was not established until 1858.

India's attraction for the British led to a much earlier founding of scientific societies and professional journals than in any other Asian country. British colonial authorities in India provided Western-style education there long before other European powers did so in the regions under their

control. In 1813, an Indian reformer with British encouragement established an English-language school for Hindu boys; this school evolved into Presidency College, Calcutta (later the University of Calcutta), and became one of India's leading sites for the growth of modern science. Two other universities, founded at Bombay and Madras by 1857, were modeled on the University of London, and maintained the same academic standards. In 1898, a wealthy Indian business leader, J. N. Tata, dispatched an associate to Europe and the United States to study the operations of universities. After many delays, but with British encouragement, his initiative led in 1911 to the founding of the Indian Institute of Science at Bangalore. It would later constitute the nucleus of the Indian Academy of Sciences. In 1859, the Jesuits established a modern university with a scientific curriculum in the Philippines, the Ateneo de Manila, and added a medical school in 1872. Similarly, Japan and China, which never came formally under European rule, managed to establish universities with programs in science at Tokyo and Peking (Beijing) in 1877 and 1898, respectively. But only later were Indian developments as a whole matched elsewhere in Asia.

Important as the legacy of European scientific activity was for the development of modern science in Asia, no sustained growth occurred before indigenous leaders assumed long-term control. Conditions varied widely from one country to another in this respect. Under the reformist Meiji regime, Japan from 1868 began to lay the foundations required for modern science in a comprehensive manner. An ultramodern engineering school opened in 1869 under the directorship of Henry Dyer, a Scot. After consulting leading scientific authorities in Europe, Japan's government began hiring young European and American scientists, engineers, and physicians at very high salaries to staff several institutions, including Tokyo University. Most importantly, a systematic program to send young Japanese to Europe and the United States for scientific and other modern studies began in 1872. After 1878, scientific societies and academic journals were established in rapid succession. By contrast, China's non-native Manchu regime only grudgingly developed a program for technical translation and modern armaments manufacture at the Kiangnan Arsenal in 1860, but scarcely went beyond it until 1898. Other needed developments—research laboratories, journals, professional societies—only appeared in the twentieth century. Thailand (then Siam) under King Chulalongkorn began to establish French-style *grand écoles* in the 1890s but had no university until 1916, and only a modest number of Thai nationals studied in Europe. Local populations in Vietnam and the East Indies (today's Indonesia) had no prospects for studying science, to say nothing of conducting research, until even later.

Parameters of Development

To what extent did the formation of a local scientific community draw effectively on traditional intellectual culture and the social structure already extant before Europeans arrived? India and Japan enjoyed relatively positive experiences in this respect. Early recruits to scientific and technical studies in India such as Chandrasekhara Raman, India's first Nobel laureate in science, and Srinivasa Ramanujan, the eminent mathematician, came from the traditional Brahmin priestly caste or the Kyasthas scholarly community. In Japan, the first generation of modern scientists (before 1920) arose predominantly from the educated samurai population inherited from the old regime (6 percent of all Japanese); Hideki Yukawa, the first Japanese Nobel laureate, came from a lin-

age of samurai Confucian scholars. In China, however, the first generation of recruits to modern science had tenuous links to traditional intellectual culture and none at all in significant numbers. This was not conducive to the establishment of modern science there.

Political independence, as opposed to colonial dependency or subjugation, was another important variable. Japan's political independence allowed it to define its own agenda, and facilitated rapid progress overall. A government of educated leaders chose which nations, institutions, and laboratories would receive the students sent to the more developed countries of Europe or (less frequently) North America. For example, they could dispatch aspiring Japanese clinicians and medical researchers to German universities at a time when Germany was preeminent in medicine. India did not have this freedom, probably one of the reasons that its modern medicine lagged behind other fields. The lack of political independence was particularly harmful in Southeast Asia. In Vietnam, the Pasteur Institute maintained a significant local research institute for tropical medicine and microbiology at Nha Trang from the 1880s, but it had almost no local educational infrastructure. Well-informed authorities such as Gaston Darboux, permanent secretary of the Académie des sciences in Paris, tried to encourage more forward-looking policies, but the retrograde views of French colonial authorities in Vietnam prevented both the permanent establishment of a university (at Hanoi) and even a permanent scientific mission of French scientists until 1917. Vietnamese had no opportunity to study modern science before 1920; some historians say that as late as 1930, the medical school had the only "serious" scientific program at the University of Hanoi. Dutch colonial authorities in the East Indies at best duplicated French science policy concerning the local population. There was no university at all in this period, only the Institute of Technology at Bandung, which opened in 1920. In 1930, Dutch nationals constituted 60 percent of its student body, Indonesians only a third.

China was neither truly independent nor formally a colony. Taking advantage of the national government's obvious weaknesses under the alien Manchu dynasty, various foreign powers began to establish protected enclaves in several parts of China, and pursued developmental agendas tailored to their own objectives. Some of their strategies favored the growth of science at a time when the Manchu regime was, at best, ambivalent and, at worst, antagonistic to it. The brief spasm of reformism that allowed the establishment of Peking University in 1898 soon spent itself; the anti-foreign Boxer Rebellion, encouraged by reactionary elements of the Manchu elite, broke out in 1900. Although China was forced to pay reparations for damage inflicted on foreign properties by the Boxers, some of this "Boxer Indemnity" was rebated (especially by the United States) to China in support of overseas study by Chinese nationals at (mostly) American universities. This program made possible the formation in 1914 of China's first professional scientific organization, the Science Society of China, a diverse organization of young aspiring scientists then enrolled at Cornell University; in 1918 they returned to China and began promoting the growth of scientific institutions and research projects by Chinese citizens.

Mass education—its presence or absence—has been important for the growth of modern science in Asia. Japan was the first Asian country to provide elementary and mid-level schooling for everyone, and its twentieth-century record in science is the continent's most impressive. India underscores the point. Mass education was only sporadi-

cally available in the country during the period of Crown Rule before 1947. Har Gobind Khorana, born in 1922 in a region now part of Pakistan, and one of only two scientists from Asia to win a Nobel Prize in medicine, had the good fortune to come from the only family in his village whose members could read and write. Yet mass education's importance should not be overstated. Partly under U.S. leadership after 1901, the Philippines achieved universal primary education not long after Japan did so; and in recent years, China appears to have followed the Philippines. Yet in technical fields during the first half of the twentieth century, the Philippines achieved only modest distinction, and that only in medicine and meteorology. The consequences of mass education for science in China cannot be evaluated yet.

The degree of political stability and the ease with which private and public interests could be deployed on behalf of scientific ventures have profoundly affected modern scientific achievement in Asia. India, Japan, and Taiwan enjoyed far greater relative stability during the twentieth century than all the other countries in the region. Stability allowed both governments and private patrons to support scientific education and research in the expectation of a positive return on their investments. The British authorities, who stabilized India, did little to support modern science in India directly, but encouraged private individuals and organizations to do so. Thus, J. N. Tata could take a significant part in founding the Indian Academy of Science, with later support from the Maharajah of Mysore, the head of one of India's princely states. Similarly, a trio of wealthy Indian lawyers raised the funds to endow chairs in physics at the University of Calcutta that supported the work of Raman and Meghnad Saha, both Nobel nominees, and one a laureate.

Japan's record in this respect parallels India's. Despite being under American military occupation from 1945 to 1952, following its defeat in World War II, Japan retained control of its own internal affairs, and generally adhered to



Indian physicist Satyendra Bose (1894–1974) is best known for his insight into the quantum property formalized as Bose-Einstein statistics.

A

policies favorable to modern science. Thus were universities founded, laboratories established, journals published, conferences held, and research conducted on a regular basis. Japan had its Imperial Academy of Sciences (founded 1906) and seven comprehensive state ("imperial") universities by 1940, as well as a host of private institutions. Taiwan and Korea, under Japanese rule from 1895 and 1910, respectively, had one imperial university each in addition to private schools. All of the state institutions and many of the private ones were active in research and teaching. Moreover, contrary to some assertions, private interests in Japan supported scientific activities at state as well as at private institutions. Two financial services executives from Osaka endowed the world's first chair of genetics, at Tokyo University, in 1918; the country's leading scientific institution of the inter-war period, the Research Institute for Physics and Chemistry (Riken), was founded in 1917 through substantial private contributions as well as state funding.

While the growth of modern science greatly benefited Japan, its military and related applications did considerable harm to the rest of Asia, with the exception of India. In Manchuria, from the time Japan seized it from China in September 1931 until the end of World War II, the Japanese army conducted research in biochemical warfare, which employed human subjects. Several thousand victims were systematically killed in the process. The U.S. Army later found the data generated sufficiently useful to justify exonerating the perpetrators. Several years before the loss of Manchuria, and after the turmoil of 1911–1927, China experienced an effective central government, which made its capital at Nanking and launched a series of reforms much like those of Japan in the late nineteenth century. During this so-called "Nanking Decade," 1928–1937, the new regime founded a science academy, the Academia Sinica, with more than a dozen research institutes, as well as a number of universities, mostly in coastal cities.

Much of this investment appeared to be lost when Japan invaded China in 1937. Many professors and university students fled to the interior to escape the conflict, taking books, journals, and research equipment with them. Some resumed their activities, at Chungking and Kunming, especially those associated with the newly constituted National Southwest University, created by merging the faculties of the transported coastal schools. Harmful as the Japanese invasion was for modern Chinese science in general, the regrouping that followed had some positive effects. Two young physicists, C. N. Yang and T. D. Lee, who met in Kunming, moved to the University of Chicago to study for their Ph.D.s in theoretical physics after the war. Working together after completing their studies, Yang and Lee surprised the international physics community by challenging the law of the conservation of parity in certain atomic reactions. For this achievement they became in 1957 the first Chinese scientists to receive the Nobel Prize. By providing them with a strong basic education in physics, China's institutional advances in the Nanking Decade and wartime years facilitated their later scientific work. What else might have been accomplished if China's political stability had matched that of India or Japan?

Contributions of Japanese and Indians to world science before 1945 include Shibasaburo Kitasato's collaboration (in 1900) with Emil von Behring on the discovery of natural immunity. During World War I, Katsusaburo Yamagiwa developed the world's first efficient means of creating cancer in the laboratory; many believe he ought at least to have shared the Nobel Prize in Physiology or Medicine for 1926.

In 1920, Meghnad Saha, a professor of physics at the University of Calcutta, published his theory of thermal ionization, a landmark achievement in modern astrophysics. Another Indian colleague, S. N. Bose, then teaching at the University of Dacca (in today's Bangladesh), made what some consider the greatest contribution of an Indian physicist to science when in 1924 he took the first major step in the formulation of quantum statistical mechanics. While Bose never won a Nobel Prize, nor was even nominated, one of the two grand classes of particles in modern physics, the bosons, is named for him. Shortly thereafter, Chandrasekhara Vankata Raman published the discovery that did win India's first Nobel in science. This so-called "Raman effect" in quantum optics found important application in spectroscopy. Published in 1928, Raman's achievement, was one of those rare instances in which an important discovery was almost immediately recognized (in this case in 1930) by a Nobel Prize.

More typical were the delays experienced by Hideki Yukawa and Shin'ichiro Tomonaga. Yukawa postulated the existence of a new particle to help explain nuclear forces in 1935, for which he received the Nobel Prize in 1949; Tomonaga solved a difficult problem in quantum electrodynamics in 1944, and shared the prize for 1964. Their candidacies developed rapidly compared with that of Raman's nephew, Subrahmanyan Chandrasekhar. Between 1930 and 1933, working in India and Cambridge, "Chandra" developed the astrophysical theory of white dwarf stars that brought him the Nobel Prize in 1983.

World War II and the Impact of Big Science

The effects of the war on science were felt as strongly in Asia as anywhere else. Seizing power in 1949, China's new Communist regime claimed to be based on scientific principles, and in its first decade appropriated Soviet models that promised a massive expansion of scientific infrastructure and research activity. Academia Sinica merged with another institution to create the powerful Chinese Academy of Sciences in 1950. New institutes and universities were founded, and emigré scientists enticed to return home. Intellectual constraints and Communist dogma offended some; surging nationalism and the dynamic expansion of the scientific enterprise excited others. During a period of relative calm in 1965, a team of biochemists in Shanghai achieved perhaps the most important modern scientific advance ever carried out in China by synthesizing bovine insulin. Seen as a harbinger of future success, the insulin achievement was soon revealed as an epitaph; China descended into the maelstrom of the Cultural Revolution the following year. Between 1966 and 1974, all the nation's universities and most of its laboratories were closed as political chaos engulfed the country.

India, Pakistan, and other Asian nations also sought progress through science after gaining independence. Several countries managed to expand the institutional base of science by building laboratories, universities, or even science academies. But few had the personnel with graduate degrees in sufficient numbers to staff these institutions at an appropriate level. Widespread poverty, illiteracy, and political instability hampered progress. The arrival of big science in the United States and Europe proved a singular spur and challenge. World War II had raised the bar for significant achievement in science, especially in physics. Raman in India wanted to undertake research in nuclear physics after the war, but had to return to optics because of a lack of resources. Abdus Salam had hoped to practice physics in his native Pakistan after completing his doctorate in 1951, but

fearing intellectual stagnation, he returned to Cambridge after three years at Lahore. His Nobel Prize came in 1979. In China, Mao had largely shielded the physicists from the destructive forces of the Cultural Revolution; partly at the urging of C. N. Yang and T. D. Lee, Mao and his successors made high-energy physics a target for investment. In 1975, the Chinese leadership endorsed a proposal from the physicists to build a 50 Ge V proton accelerator. Comparable to some earlier accelerators in Europe and the United States, the facility would have brought China welcome prestige. However, the cost of the project and disagreements among likely users led to its termination in the early 1980s.

Because of earlier progress and relative stability, India and Pakistan developed faster than most other Asian countries. Jawaharlal Nehru's prime ministership, 1947–1964, gave India both a rhetorical and a substantive commitment to science that fully matched the new regime of Mao in China but without the cross-currents of revolutionary politics. Nehru's commitment to science expressed itself partly in the foundation of the campuses of the Indian Institute of Technology in five Indian cities with support from Indian and other governments. Focusing primarily on undergraduate education but with some research programs, these schools took MIT as a model, and were widely seen to produce graduates of comparable quality. In a major private initiative of the period, one of Nehru's leading scientific advisers, the physicist Homi Bhabha, persuaded the Tata family to establish the Tata Institute for Fundamental Research at Bombay.

Big science stretched even Japan's resources. Its economy began to recover from the war in late 1950, but the country spent at only half the level of Western Europe on science for the next two decades. Leo Esaki's career in this period illustrates the situation. In 1958, he discovered the tunneling effect in semiconductors while working as a graduate student for the firm that later became Sony. A shared Nobel Prize came to him for this work in 1973, but he worked in the United States after 1960. Susumu Tonegawa's research career followed a similar pattern. After earning a Ph.D. in molecular biology at the University of California, San Diego, he moved to Switzerland, and there investigated the genetic origins of antibody diversity that in 1987 made him the first Japanese recipient of a Nobel Prize in medicine. He was at the time, and has remained, a professor at MIT. Ken'ichi Fukui, however, stayed in Japan, studying chemical reaction theory at Kyoto University. By applying quantum theory to knowledge of hydrocarbons gleaned from wartime work on synthetic fuels, he became in 1981 the first scientist in Asia to win the chemistry Nobel Prize (shared with Roald Hoffmann). In 1984, Y. T. Lee, from Japan's former colony of Taiwan, also won in chemistry, for work done at the University of California, Berkeley.

Only after 1970 did Japan begin to extend the level of support for science long provided by the affluent nations. The founding of Tsukuba University and the Tsukuba Science City in the early 1970s exemplified the new commitment by providing equipment and facilities well beyond those of Japan's other institutions. After 1980, it appeared that Japan intended to raise its level of accomplishment in science, and after 1990 it made explicit declarations to that effect. Convinced by these declarations, Leo Esaki accepted the presidency of Tsukuba University in 1992. Japan's business establishment added weight to expectations by publicly advocating huge increases in funding for research in academic institutions. For Esaki and the Japanese establishment, securing more Nobel Prizes in science became both

a public aspiration and a symbolic obsession. Specific initiatives such as the annual Japanese Forum of Nobel Prize Recipients were launched to fulfill this objective. In 2000, a retired professor from Tsukuba University, Hideki Shirakawa, received a share of the Nobel Prize in chemistry for his work on conducting polymers. The following year, another Japanese chemist, Ryoji Noyori, also won in chemistry.

Japan's accomplishments and greater wealth in the region have elicited significant responses on behalf of science in other East Asian nations. South Korea, Taiwan, and Singapore in particular have built substantial new research facilities in recent years, although most have emphasized applied rather than basic science. There is a strong conviction in Asia that greater investment in science will promote more rapid economic growth, as well as cultural prestige. Several nations have launched formal programs to induce emigré nationals to return. In 1957, Chinese authorities tried to persuade C. N. Yang to leave the United States and return to China while he was in Stockholm receiving his Nobel Prize. But few of the efforts succeeded before the early 1990s, when Taiwan successfully invited Y. T. Lee to leave Berkeley to lead Academia Sinica (1993) and Japan enticed Esaki to take the presidency at Tsukuba (1992). Although wealth does not in itself lead directly to distinguished achievement in science, the era of big science makes wealth essential. The major economic reforms set in train by India, China, and other Asian countries in recent years should further raise their collective profile in science.

JAMES R. BARTHOLOMEW

ASTROLABE. The astrolabe is an astronomical and astrological instrument used for calculations involving the positions of the stars and the sun. Although based on the assumption of a spherical sky in daily rotation around a central earth, almost all astrolabes are flat.

The traditional form of astrolabe has a circular, planispheric map of the stars known as the "rete" (Latin for "net"). This star-chart usually takes the form of a brass plate with most of the metal cut away by fretwork, leaving a network of bands supporting pointers indicating the positions of the stars, and a circular band for the annual path of the sun through the stars, known as the ecliptic. The plane of projection coincides with the equator, while the rectilinear projection lines converge at the south celestial pole. The same projection renders the local horizon of the user, and circles of altitude and azimuth, on a solid brass disc the same size as the rete. These projected lines form the characteristic pattern of the "latitude plate," where circles and arcs cluster around the point that indicates the local zenith, while arcs of azimuth radiate out from it. Both projections extend from the north celestial pole, usually to the tropic of Capricorn. The rete, pivoted at the pole, rotates above the stationary latitude plate; adjusted to any orientation of the sky it will indicate the positions of the stars or the sun above the horizon. Since the position of the sun in its daily rotation measures the time, an hour scale at the edge of the instrument can give the time at any hour of day and night: a rule pivoted at the center carries the sun's position (indicated by a date or zodiac scale on the ecliptic ring) to the hour scale. On the back of the astrolabe is an alidade, or sighting rule, with an altitude scale, for measuring the altitude of the sun or one of the stars included on the rete. By this means the rete can be set to the current position of the sky and the time found. Other scales on the front and back of the instrument allow astrolabes to perform a range of different functions.

A

Ptolemy described the geometrical basis of the traditional instrument. The earliest surviving astrolabes come from ninth-century Baghdad and Iran. The earliest dated European ones come from the fourteenth century, though astrolabes from several centuries earlier have survived. In the traditional form, separate projections are given for different latitudes, so instruments often have a number of alternative latitude plates. Muslim astronomers found several ways of making a “universal” astrolabe—one that would serve in any latitude—and Europeans devised or rediscovered similar designs in the sixteenth century. The European instrument was in rapid decline by the early seventeenth century, but fine astrolabes continued to be made in parts of the Islamic world through the nineteenth century. Astrolabes have always been treasured and admired, and they remain one of the most desirable instruments for collectors today.

The mariner’s astrolabe, by contrast with the complex and ornate instruments for astronomy and astrology, had a simple and robust design. Combining an altitude ring and an alidade, they were used for finding latitude at sea mainly in the sixteenth and early seventeenth centuries).

JIM BENNETT

ASTROLOGY. Astrology is best defined as the set of theories and practices interpreting the positions of the heavenly bodies in terms of human and terrestrial implications. (The positions have variously been considered signs and, more controversially, causes.) The subject—and therefore its study—is fascinating, difficult, and often paradoxical. Although inextricably entangled with what are now demarcated as science, magic, religion, politics, psychology, and so on, astrology cannot be reduced to any of these. The historical longevity and cultural diversity of astrology are far too great for it to have been precisely the same thing in all

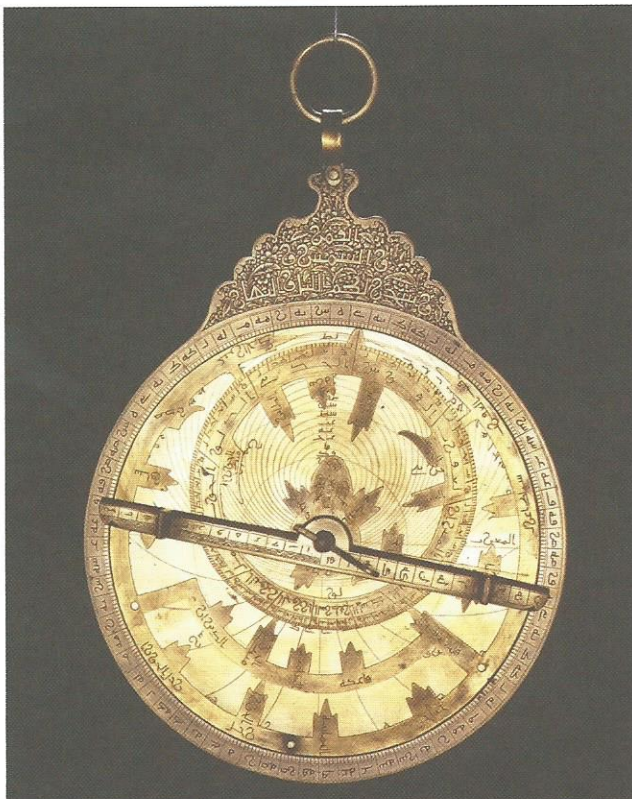
times and places, yet it has always managed to reconstitute itself as much the same thing in the minds of its practitioners, public, and opponents alike. These points have particular relevance in relation to historians of science, who until recent decades predominantly analyzed astrology anachronistically as a “pseudo-science,” the human meanings of which could largely be derived from its lack of epistemological credentials.

Western astrology originated as Mesopotamian astral divination. The planets and prominent stars, identified with gods in ways that have since changed remarkably little, were considered celestial omens in which the divine messages, largely answering royal concerns, could be discerned. The origins of many key elements of the astrological tradition—not only the planetary deities, zodiacal signs, risings, and settings, but also the effort to systematize divination through what we would now consider astronomical and empirical observations—developed between its apparent origins around 2000 B.C. and the fifth century B.C., when natal astrology first appeared. The latter, following Alexander’s conquest of Persia, was absorbed and transformed by Greek geometric and kinetic models, which added the aspects, or angles of separation between planets and points, and emphasized the importance of the *horoscopus* or Ascendent, the degree of the zodiacal sign rising on the Eastern horizon. (The first known horoscope dates from 4 B.C.) Astrology was also fruitfully married to Aristotelian cosmology and Greek medicine in the form of Hippocratic humors, and, slightly later, Galenic temperaments. Astrologers tended to develop increasingly flexible interpretive schemes, of which the most famous and influential was formulated by Ptolemy (c. A.D. 100–170) in his *Tetrabiblos*.

Astrology played an important role in Roman life, for the most part in crudely populist and overtly political contexts. A more fruitful course followed in the wake of Alexander the Great’s conquests, as Greek astrology spread to Persia and throughout Eastern Asia as far as India. In this way Greek astrology eventually became incorporated into, and benefited from, the learning of the Arabic world. It was introduced into medieval Europe in Latin translations, notably, from the mid-twelfth century onwards, of works by Abu Ma’shar (787–886). These supplied a philosophical basis (largely Aristotelian) for astrology and popularized the idea that conjunctions of Jupiter and Saturn (“grand conjunctions”) in particular regions of the heavens signify changes of political rulership. A complete revolution of the conjunctions around the zodiac, which takes 960 years, indicated changes in the fortunes of entire religions. Pierre d’Ailly and Roger Bacon took up this astral historiography.

In the late fifteenth century, a series of influential translations by Marsilio Ficino made available rediscovered Greek texts, including much of Plato, Plotinus, and Iamblichus and the *Corpus Hermeticum*. These placed a renewed magical and/or mystical astrology at the heart of the Renaissance revival of neo-Platonism and hermeticism. Typically, it managed to evade Giovanni Pico della Mirandola’s powerful critique of astrology in his *Disputationes* (1494) by finding shelter elsewhere in the set of ideas that had inspired him (for example, occult sympathy and antipathy).

Astrology was controversial within the Christian church. It survived the condemnations of St. Augustine and the early church fathers, who saw it as pagan (and in particular polytheistic) and a transgression of both human free will and divine omnipotence. Augustine did not deny that astrologers could speak truthfully, only that when they did so it was with the help of, and in the service of, demons.



Islamic astrolabe made between 1350 and 1450. The top, cut-out plate is the rete; a latitude plate appears beneath and through it.

At both popular and elite levels, however, astrology in one form or another remained entrenched. It fell to Thomas Aquinas in the late thirteenth century to arrange a compromise that secured for it a long-lived, if limited, niche. His synthesis of Christian theology and Aristotelian natural philosophy permitted “natural astrology” to influence physical and collective phenomena but not human souls directly; the individual judgments (and in particular predictions) of “judicial astrology” were therefore illicit. Since Aquinas admitted that most people followed the promptings of their bodies, which felt the influence of the stars, he gave a tacit legitimization of astrology in practice. But the Reformation presented a serious new challenge in the sixteenth century. Luther and Calvin objected violently to astrology’s idolatry, as they saw it, which they stigmatized as “superstition.”

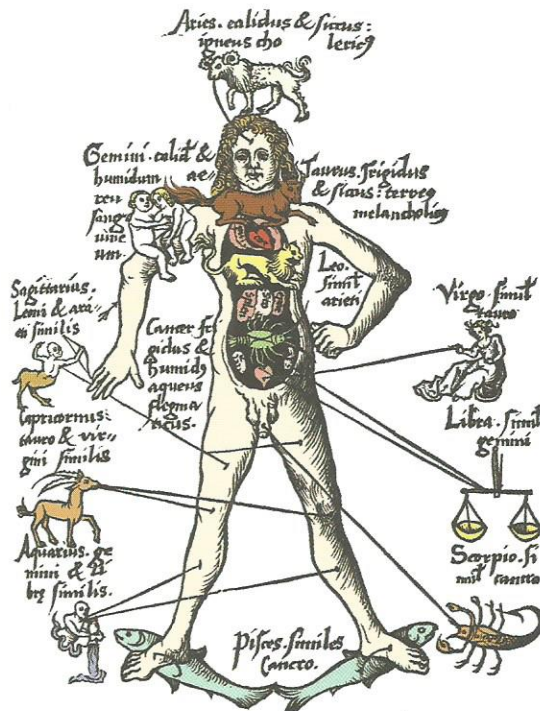
The seventeenth century was pivotal in the history of astrology. Contrary to the argument of Keith Thomas’s influential *Religion and the Decline of Magic* (1971), the historical puzzle is not why so many intelligent people then believed in astrology (at a time when most people did), but why did they cease to believe in it?

Strong social and political forces abetted its fall from favor. In the English Revolution the pamphlets and almanacs of astrologers on both sides—but especially those of William Lilly for Parliament—played a major, and highly visible, role. In the late seventeenth and eighteenth centuries the new patrician and commercial alliance sought to put sectarian strife and upheaval behind it, and astrology became firmly identified as vulgar plebeian (rather than religious) superstition, to be contrasted with the spirit of rationalism and realism. This perception was now most often articulated by a new set of opponents: the metropolitan literati. Jonathan Swift’s issue of a mock almanac in 1707 predicting the death of the prominent astrologer John Partridge, followed by another putatively confirming its fulfilment, epitomized the attack. Partridge became a laughing-stock in coffeehouse circles, although his almanacs continued to sell. Benjamin Franklin later employed the same tactic in the American colonies.

At the same time, increasing political centralization in France made astrologers’ unlicensed prophecies unwelcome there too. After a short period of ambivalence, most prominent European natural philosophers also started to close ranks against astrology, ignoring or criticizing it as part of the old Aristotelian order, and/or as (plebeian or Platonic) magic. Isaac Newton’s success set the seal on this development. He borrowed the old idea of attraction at a distance, but substituted a single and quantifiable force for an astrological sine qua non: the planets as a qualitative plurality. Natural philosophy quietly absorbed natural astrology (including the moon’s effects on tides), but judicial astrology, as a symbolic rather than mathematical system addressing merely “secondary” qualities and “subjective” concerns, had no place in a newly disenchanted (and commodified) world.

In this context the charge against astrology of “superstition” began to acquire its present meaning as a cognate of stupidity or ignorance. To begin with, natural philosophers made common cause with the guardians of religious orthodoxy; but as natural philosophy moved in the direction of modern science, the hostility to astrology increasingly became a secular opposition.

The early modern period has too often been described, by those mistaking contemporary rhetoric for reality, as the time of the death of astrology. It did decline seriously as it was pushed into largely (but not entirely) rural strongholds dominated by farmers’ almanacs, and into a relatively sim-



Correspondences between zodiacal signs and body parts; doctors did not bleed patients from a part in whose sign the moon stood. From the popular encyclopedia *Margarita philosophica* (1503) by Gregor Reisch.

ple and magical set of beliefs. But early in the nineteenth century, as the middle classes grew in power and began to break away from patrician hegemony, a new urban astrology appeared that still remains. More individualistic than before, it succeeded in adapting to consumer capitalist society. And in the early twentieth century, through the work of Alan Leo and his commercially canny Theosophy, astrology secured a firm footing in both the popular press and the thriving middle-class market for psychology-cum-spirituality. At present it seems to meet a demand for (re-)enchantment that no amount of technical, technological, or purely theoretical progress can serve.

Thus astrology has managed to adapt to, and even exploit, every challenge history has thrown it. There is no reason to expect it will ever fail to do so, despite the outraged denunciations it continues to attract from contemporary guardians of scientific probity.

PATRICK CURRY

ASTRONOMY. Astronomy, unlike modern sciences formed during the Scientific Revolution of the seventeenth century, has an ancient pedigree. The goals of astronomers, however—their theories, their instruments and techniques, their training, their places of work, and their sources of patronage—have undergone changes as revolutionary as those experienced by other sciences over the past four centuries.

For two millennia before the seventeenth century, a primary problem for astronomy in the Western world was to discover the true system of uniform circular motions believed to underlie the observed and seemingly irregular motions of the planets, Sun, and Moon. Astronomers observed and recorded a few planetary, solar, and lunar positions; attempted to fit geometrical models to the observations; and constructed tables of positions. In addition to the effort for its own sake, there were practical offshoots, including personal horoscopes, more general warnings of man-made

and natural catastrophes, and calendars foretelling times of religious celebrations and the agricultural seasons. Solar and stellar navigation became important only later; fourteenth- and fifteenth-century explorers still found their way in sight of land. The rest of the universe scarcely existed for ancient and medieval astronomers other than as the limiting outer sphere of the stars. Nor did they concern themselves with the physical composition of the universe. Beyond the region of the Earth lay one unchanging element.

The Copernican Revolution, begun in the sixteenth century, switched the places of the Earth and the Sun in a geometrical model still composed of uniform circular motions. In other important ways, however, Copernicus radically redefined the astronomical agenda. After new observations refuted the ancient assumption of circular motion, the physical nature and cause of orbital motion, previously outside the province of astronomers, became crucial. Interest in the physical composition of the heavens increased as well once the Earth left the center of the universe, and especially after Galileo's revolutionary new telescopic observations.

In 1609 rumor from Holland of a device using pieces of curved glass to make distant objects on the Earth appear near reached Galileo in Italy. He constructed his own telescope and turned it on the heavens. Among his discoveries were four moons circling Jupiter. These Medicean stars, as he named them, secured him a position at the court of the Grand Duke of Tuscany. Galileo also observed mountains on the Moon and sunspots. Henceforth the telescopic discovery of hitherto unknown planets, moons, asteroids, comets, and nebulae, as well as examination of their more prominent activities, was a standard feature of astronomers. Amateurs wealthy enough to procure relatively large telescopes could excel.

The telescope became an instrument of precise measurement through a happy accident. Noticing that a spider's web spun in the focal plane of his telescope was superimposed on the telescopic image, the Englishman William Gascoigne realized that crosshairs or wires could help center telescopes on objects and also help measure angles between them. By 1700, after some resistance, astronomers had accepted the telescope as the primary instrument of astronomical measurement. The cost of larger telescopes, their operation, and analysis of data speeded the transition from individual observers to organized observatories under government patronage. The Paris Observatory was founded as part of the new Paris Academy of Sciences in 1666, and the Greenwich Observatory began operations a decade later. In a new age of exploration, the task of the Greenwich Observatory, as stated in a royal warrant, was to rectify "the tables of the motions of the heavens, and the places of the fixed stars, so as to find out the so much-desired longitude of places for the perfecting the art of navigation."

The last great achievement of pre-telescopic observations was Tycho Brahe's body of positional measurements at the end of the sixteenth century. He enjoyed inherited wealth and also royal patronage, given in exchange for the glory his discoveries and fame cast over his patrons. Early in the seventeenth century, Johannes Kepler used Brahe's positions to destroy faith in uniform circular motion, showing instead that ellipses more accurately describe planetary motions around the Sun. Aristotelian physics, explaining all motion around a central Earth, did not work in a Sun-centered universe. An explanation of why the planets retrace their elliptical paths around the Sun became a central problem of astronomy.

Near the end of the seventeenth century, Isaac Newton treated celestial motions as problems in mechanics governed

by the same laws that determined terrestrial motions. Bodies remain at rest or move uniformly in straight lines unless external forces alter their state. A force of attraction toward the Sun continually draws the planets away from rectilinear paths and holds them in their orbits. Newton showed mathematically that, on his mechanical principles, Kepler's elliptical orbits result from a universal inverse-square law of gravity. The working out of details left undone by Newton focused the energies of many mathematical astronomers during the eighteenth century. Newtonians added quantitative success upon success, though not in the form Newton himself had used. Newton had employed geometry, the accepted medium of mathematical proof, in his demonstrations. His successors used new, more powerful algebraic methods. This change may help explain why Newton's loyal followers in England made little progress compared to scientists on the continent. Royal academies with generous support for astronomers, particularly at Paris, Berlin, and St. Petersburg, also made a difference. London's Royal Society, in contrast, neither received nor paid out royal emoluments, and the astronomers royal at Greenwich had to provide some of their own instruments.

Exact orbital calculations incorporate the influence of small perturbation effects. The Sun alters the Moon's motion around the Earth, and Jupiter and Saturn modify the motions of each other about the Sun. The Swiss-born mathematician Leonhard Euler, at St. Petersburg and later at the Berlin Academy of Sciences, helped develop mathematical techniques to compute perturbation effects. He applied them first to the Moon, and in 1748 to Jupiter and Saturn, whose motions were the subject of that year's prize topic of the Paris Academy of Sciences. Euler, and Joseph Louis Lagrange and Pierre-Simon Laplace, both members of the Paris Academy, applied the newly all-powerful calculus to the perturbations of planets and satellites, the motions of comets, the shape of the Earth, precession (a slow conical motion of the Earth's axis of rotation caused primarily by the gravitational pull of the Sun and the Moon on the Earth's equatorial bulge), and nutation (a smaller wobble superimposed on the precessional motion of the Earth's axis).

Orbital calculations now lie outside mainstream astronomy. NASA scientists use computers to calculate trajectories for their spacecraft. Astronomers would be willing, for additional government funding, to calculate whether various passing asteroids will safely miss the Earth.

The business of astronomy has at times been a family profession. Gian Domenico Cassini, recruited from Italy to set up the Paris Observatory in 1669, was succeeded by a son, a grandson, and a great-grandson, before the French Revolution drove the family from the observatory in 1793. Friedrich Struve, who helped Czar Nicholas I chart his vast empire and also recorded the positions of double stars at the Pulkovo Observatory, opened in 1839 outside St. Petersburg, founded an astronomical dynasty spanning four generations. A son succeeded him at Pulkovo, a grandson directed the Königsberg Observatory, and a great-grandson, having fled Russia in 1921 after the revolution, directed the Yerkes Observatory of the University of Chicago and then, in the 1950s, the astronomy department of the University of California.

In the middle of the nineteenth century, the Pulkovo Observatory shared the honor of possessing the largest refracting telescope in the world. Refractors bend to a focus light passing through curved glass lenses. As late as the end of the eighteenth century, glass of the quality necessary for

optical instruments could be cast only in small pieces, up to two or three inches in diameter. The English duty on manufacturing limited production and made further experimentation too costly. Progress occurred on the continent, but even there the largest lens achieved by 1824 was a 9.5-inch disc for the Dorpat Observatory (in what is now Tartu, Estonia). In 1847 the 15-inch refractors at Pulkovo and the Harvard College Observatory were the largest in the world.

British industry made possible the first large reflecting telescope (1780 to 1860), which used metal mirrors to reflect light to a focus. William Herschel built a 48-inch metal mirror in 1789; in 1845 William Parsons, the Earl of Rosse, completed in Ireland his “leviathan,” which had a metal mirror 72 inches in diameter. Large reflectors with their tremendous light-gathering power yielded remarkable observations of distant stellar conglomerations. But difficulty in aiming tons of metal and rapid tarnishing of mirrors rendered early reflectors unsuitable for observatories and professional astronomers, who could not harness consistently the instrument’s raw power. Something new arrived with the twentieth century: a 60-inch reflecting telescope built and installed at the new Mount Wilson Observatory in 1908. The telescope had a reflective silver coating on a glass disc ground to bring incoming light to a focus, and a mounting system and drive capable of keeping the multiton instrument fixed on a celestial object while the Earth turned beneath it. The mountain observatory, funded by Andrew Carnegie’s philanthropic Carnegie Institution, was one of the first located above most of the Earth’s obscuring atmosphere. Its reflecting telescope, specifically designed for photographic work, completed the revolution in astronomical practice—which had required the tedious drawing by hand of features seen through telescopes—begun with the invention of photography.

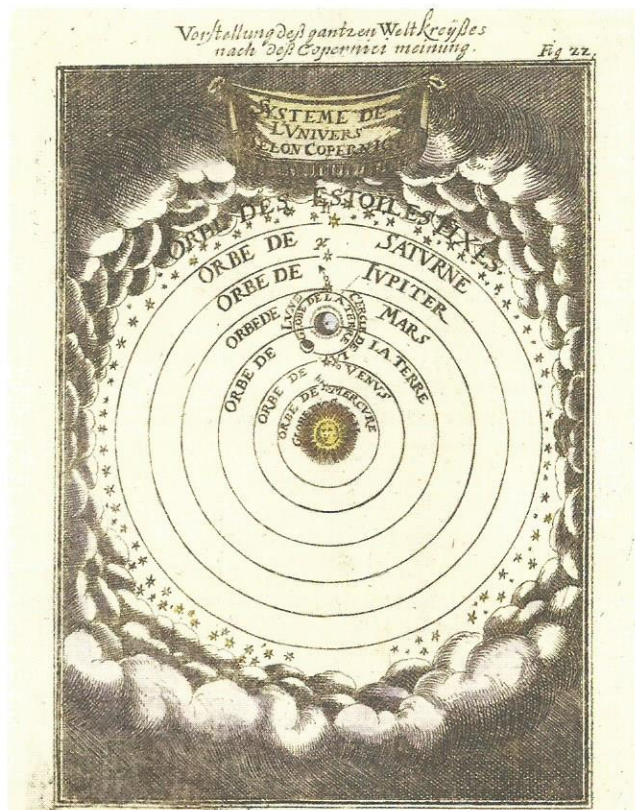
With professional astronomers by definition already employed in research projects, amateur astronomers pioneered in applying photography. The American John Draper took the first known photograph of a celestial object, the Moon, in the 1840s. In 1851 a new process using plates exposed in a wet condition made possible a few photographs of the brightest stars, but not until the introduction of more sensitive dry plates after 1878 did photography become common in astronomical studies. Draper’s son Henry took the first photograph of a nebula, the Orion Nebula, in 1880. In England long exposures taken by Andrew Common and Isaac Roberts brought out details too faint for the eye to see. Photography facilitated comparisons over time, produced permanent recordings of positions suitable for more precise measurement, and was essential for exploitation of the other new astronomical tool of the nineteenth century, spectroscopy.

The development of spectroscopy and the subsequent rise of the new science of astrophysics created new activities for astronomers. When attached to telescopes, prisms splitting light into spectra opened up investigation of the physical and chemical nature of stars. In 1859 Gustav Kirchhoff, professor of physics at Heidelberg, showed that each element produces its own pattern of spectral lines. In the first qualitative chemical analysis of a celestial body, he compared the sun’s spectrum to laboratory spectra. The English amateur astronomer William Huggins seized on news of Kirchhoff’s work. By 1870 he had identified several elements in spectra of stars and nebulae. He also measured motions of stars revealed by slight shifts of spectral lines. Early in the twentieth century Vesto M. Slipher at the Lowell Observatory in Arizona was the first to measure Doppler shifts in spectra of faint spiral nebulae, whose receding motions revealed the

expansion of the universe. It required an extended photographic exposure over three nights to capture enough light for the measurement.

Astronomical entrepreneurship late in the nineteenth century saw the construction of new and larger instruments and a shift of the center of spectroscopic research from England to the United States. Charles Yerkes and James Lick put up the funds for their eponymous observatories, which came under the direction, respectively, of the University of Chicago and the University of California. Percival Lowell directed his own observatory in Arizona. All three observatories were far removed from cities; the latter two sit on mountain peaks.

A scientific education became necessary for professional astronomers in the later nineteenth century, as astrophysics came to predominate and the concerns of professionals and amateurs diverged. As late as the 1870s and 1880s the self-educated American astronomer Edward Emerson Barnard, an observaholic with indefatigable energy and sharp eyes, could earn a place for himself at the Lick and Yerkes observatories with his visual observations of planetary details and his discovery of comets and the fifth satellite of Jupiter, but he was an exception and an anachronism. A project begun in 1886 at the Harvard College Observatory and continued well into the twentieth century to obtain photographs and catalog stellar spectra furthered another social shift in astronomy. It employed women, for lower wages than men would have received, but at least made space for them in a male profession. Annie Jump Cannon was largely responsible for the Henry Draper Catalogue, published between 1918 and 1924, which gave spectral type and magnitude for some 225,000 stars. Also, she rearranged the previous order of spectra into one with progressive changes in the appear-



The Copernican system, with the Sun in the center of the solar system. The earth has its moon, but Jupiter still lacks its satellites.



Edwin Powell Hubble (1889–1953), US astronomer and cosmologist, first demonstrated the existence of galaxies outside our own.

ance of the spectral lines. Although she developed her spectral sequence without any theory in mind, astronomers quickly realized that changes in the strength of hydrogen lines indicated decreasing surface temperature.

Spectral class became even more useful when, early in the twentieth century, it was related to luminosity. The relationship could be used to estimate distances. Students of stellar evolution asked what in the constitution of stars gave rise to dwarfs and giants and why brightness increased systematically with spectral type. The source of stellar energy, and with it the constitution of stars, became better known after the discovery of radioactivity at the beginning of the twentieth century. As late as 1920, however, the English astrophysicist Arthur Eddington complained that the inertia of tradition was delaying acceptance of the most likely source of stellar energy: the fusion of hydrogen into helium. Eddington calculated how fast pressure increases downward into a star and how fast temperature increases to withstand the pressure. He used qualitative physical laws regarding the ionization of elements developed in the 1920s by Meghnad Saha, an Indian nuclear physicist. Saha's work also provided a theoretical basis for relating the spectral classes of stars to surface temperatures. World War II produced a deeper understanding of nuclear physics and more powerful computational techniques. The practice of astrophysics has moved from observatories to scientific laboratories to giant computers running simulations.

Cosmology, the study of the structure and evolution of the universe, only belatedly insinuated itself into modern mainstream astronomy. An inability to measure great distances limited cosmology for centuries to philosophical speculations, often focused on the nature of nebulae and the possible existence of island universes similar to our galaxy. Cosmology achieved an observational foundation early in the twentieth century, when Harlow Shapley and Edwin

Hubble at the Mount Wilson Observatory made the observations that revealed the size of our galaxy, the existence of other galaxies, and the expansion of the universe.

At first these observations made little connection with Einstein's relativity theory. Astronomers, especially in the United States, possessed only limited mathematical knowledge, and were largely content to produce observations while leaving theory to theoreticians. In England, in contrast, interest in relativity theory relatively flourished. But the work was strictly mathematical, without observational input. In the 1930s, Hubble attempted to bridge the gulf between observation and theory. Cooperation, he wrote, featured prominently in nebular research at the Mount Wilson Observatory, and he struck up a close collaboration with colleagues at the nearby California Institute of Technology. Not until the 1960s, however, after the discovery of quasars and the intense theoretical effort to find a new energy source to explain them, did relativity theory secure a place in mainstream astronomy.

During the 1970s and 1980s, scientists realized that important cosmological features could be explained as natural and inevitable consequences of new theories of elementary particle physics, and particle physics now increasingly drives cosmology. Also, particle physicists, having exhausted the limits of particle accelerators and public funding for yet larger instruments, now turn to cosmology for information regarding the behavior of matter under extreme conditions, such as prevailed in the early universe.

The greatest change in astronomy during the twentieth century in understanding the universe and also in the backgrounds of astronomers and their activities followed from observations beyond visual light. In the 1930s, the American radio engineer Karl Jansky and the radio amateur Grote Reber pioneered detection of radio emissions from celestial phenomena, and radar research during World War II helped develop radio astronomy, especially in England. X-ray astronomy also took off after the war, first aboard captured German V-2 rockets carrying detectors above the Earth's absorbing atmosphere. NASA subsequently funded a rocket survey program and then satellites to detect X rays. Most of the new X-ray astronomers came over from experimental physics with expertise in designing and building instruments to detect high-energy particles. Their discoveries followed from technological innovations. Gamma rays and infrared and ultraviolet light provided further means of non-optical discoveries in the space age. Unlike the relatively quiescent universe open to Earth-bound astronomers' visual observations, the universe newly revealed to engineers and physicists observing at other wavelengths from satellites is violently energetic.

NORRIS S. HETHERINGTON

ASTRONOMY, NON-OPTICAL. Many recent astronomical discoveries have been made without using visible light. The newly revealed universe is fascinating in its activity. Stars are born, galaxies collide, neutron stars collapse into black holes, quasars vary in hours through luminosities greater than that of our entire galaxy, and pulsars rotate gigantic radio beams in fractions of seconds.

Radio astronomy is the oldest branch of the new astronomy. In 1932, Karl Jansky, an American radio engineer with the Bell Telephone Company, detected electrical emissions from the center of our galaxy while studying sources of radio noise. Neither optical astronomers nor Jansky's practical-minded supervisors cared. Grote Reber, an ardent radio amateur and distance-communication addict, took an inter-

est, and built for a few thousand dollars a pointable radio antenna 31 feet in diameter in his backyard in Wheaton, Illinois. In 1940, he reported the intensity of radio sources at different positions in the sky.

Fundamental knowledge underlying radio astronomy techniques increased during World War II, especially with research on radar, and especially in England. After the war, research programs at Cambridge, at Manchester, and at Sydney, Australia, dominated radio astronomy for the next decade.

Manchester's large steerable radio telescope at Jodrell Bank was rescued from financial disaster in 1958 by its ability to track *Sputnik*. Other uses floated had included mobilizing the telescope as part of a ballistic missile tracking system and for long-range bomber navigation. As an astronomical instrument it detected radar signals bounced off ionized meteor trails in the earth's atmosphere. Other scientists bounced radar signals off the Moon and developed planetary radar astronomy to map the surfaces of planets.

The program at Cambridge was led by Martin Ryle, who received a Nobel Prize in 1974 for his overall contributions to radio astronomy. He completed a survey of almost two thousand radio sources, most of them extragalactic, in 1955. These sources had a bearing on Fred Hoyle's steady-state cosmological theory. Within a few years radio data and their interpretation were more certain, and argued convincingly against Hoyle's cosmology, which allowed for fewer faint radio sources than were detected.

The major blow to Hoyle's theory came in 1965 with discovery of the cosmic microwave (short radio wave) background radiation. It had been predicted in 1948 by nuclear physicists exploring the consequences of the cosmological big bang, but no astronomer looked for it. In 1963, Arno Penzias and Robert Wilson with the Bell Telephone Laboratories detected what the first regarded as noise in an antenna, but soon realized must be excess radiation of cosmic origin. In 1965, Robert Dicke at Princeton interpreted the work for which Penzias and Wilson received a Nobel Prize as a remote consequence of the origin of the universe.

Radio sources were identified in the early 1960s with star-like objects, now called quasi-stellar objects, or quasars. They have luminosities a thousand times that of our entire galaxy. The only known source for so much energy from such a small volume is a black hole. Quasars also have extremely large red shifts, probably a manifestation of an expanding universe. Ryle shared the Nobel Prize with his Cambridge colleague Anthony Hewish, who was credited with discovering pulsating radio sources, although his student Jocelyn Bell made the actual observation, in 1967.

Radio astronomy is increasingly threatened by modern society's growing use of garage-door openers, microwave ovens, wireless telephones, and other sources of interference with radio signals from astronomical objects. The commercial use of radio frequencies is light pollution's invisible cousin.

As did radio astronomy, X-ray astronomy also took off after World War II, first aboard captured German V-2 rockets that took detectors above the earth's absorbing atmosphere. Herbert Friedman at the U.S. Naval Research Laboratory found that the Sun weakly emits X rays, as expected. Astronomers did not expect to find strong X-ray sources, and doubted that brief and expensive rocket-borne experiments could contribute much to observational astronomy. In the immediate post-*Sputnik* period, however, more government money existed for astronomical research than imaginative scientists could spend.

Help came from Italian-born Riccardo Giacconi, who worked at the private company American Science and Engineering and then at the Harvard-Smithsonian Observatory before becoming director of the Space Telescope Science Institute. In 1960, with funding from the Air Force Cambridge Research Laboratories, Giacconi discovered the first cosmic X-ray source, Sco X-1 (the strongest X-ray source in the constellation Scorpius). In 1963, Friedman's group detected a second strong X-ray source, associated with the Crab nebula, the remnant of a supernova explosion.

NASA now funded a rocket survey program and a small satellite devoted exclusively to X-ray astronomy. Launched into an equatorial orbit from Kenya on its independence day in 1970, the satellite was nicknamed *Uhuru*, Swahili for freedom. Its detectors discovered binary X-ray pulsars, neutron stars whose energies arise from infalling matter from companion stars. The Einstein X-ray telescope, launched in 1978, revealed that individual sources account for much of the X-ray background radiation. Giacconi had wanted to name this satellite *Pequod*, from Melville's *Moby Dick*, as a reminder of Massachusetts and the American Indian. The inevitable comparisons of Giacconi and the egomaniacal Captain Ahab indicate the qualities needed to drive a large and complex scientific project to completion. NASA declined to associate its satellite with a white whale.

A single scientific paper was published on X-ray astronomy in 1962, and 311 a decade later. Only 4 out of 507 American astronomers participated in X-ray astronomy in 1962, compared to 170 out of 1,518 in 1972. Over 80 percent of the participants came from experimental physics with expertise in designing and building instruments to detect high-energy particles.

More energetic than X rays, gamma rays arise from nuclear reactions, including those that create elements in stars and bombs. A satellite watching for nuclear tests in the atmosphere made the first observation of cosmic gamma ray sources in 1973. The Compton Gamma Ray Observatory, deployed from a U.S. space shuttle in 1991, has recorded bursts of gamma radiation, about one a day, perhaps from mergers of extremely distant neutron stars into black holes. Gravitational waves from these events may be detectable by the Laser Interferometric Gravitational-wave Observatory, constructed in 1999. The final seconds of such an event would be more luminous than a million galaxies. If it occurred in our galaxy, the burst of gamma radiation would destroy the earth's ozone layer, kill all life on Earth, and leave the earth's surface radioactive for thousands of years.

The ultraviolet is relatively quiet. The Extreme Ultraviolet Explorer Satellite, launched in 1992, has observed hot plasma flares in the outer regions of a few nearby stars. Much of the interstellar medium, however, stops ultraviolet light. The Hubble Space Telescope spans the spectral region from far-ultraviolet through visible to near-infrared.

Cool stars, planets, grains of dust in interstellar space, and also animals radiate most of their energy at infrared frequencies. Frank Low at Texas Instruments developed an infrared detector in 1961 so sensitive that under the impossible ideal condition of no other interfering infrared source, and hooked up to the world's largest telescope, it could have detected the body heat of a mouse on the Moon. Carl Sagan wanted to use it to beat the Russians in the race to detect life on Mars. In 1967 Low, now at the Kitt Peak National Observatory in Arizona, discovered a giant cloud of gas and dust in the constellation of Orion invisible at optical wave-

A
lengths but emitting enormous energy in the infrared. The cloud might be an interstellar nursery in which stars are born and grow in their violent way. The Infrared Astronomical Satellite during ten months in 1983 before all its cooling helium evaporated found more extensive dust tails for comets than are visible optically, rings of dust in our solar system, and an extensive ring or shell of gas and dust around the star Vega, perhaps left over from the original cloud of gas and dust from which Vega condensed.

The recent revolution in non-optical astronomy has important policy lessons. Should bureaucrats follow Thomas Kuhn's theory of the structure of scientific revolutions and act as keepers of the paradigm, directing research funds into observations intended to extend and consolidate mature theories? Or should they favor the early stages of development of new fields, when practitioners fumble along without any fixed conceptual framework? Non-optical astronomical discoveries have followed largely from technological innovations, with little advance prediction or justification for their search. Is it, then, nobler of mind and more cost-efficient to serve old paradigms or new technologies?

NORRIS S. HETHERINGTON

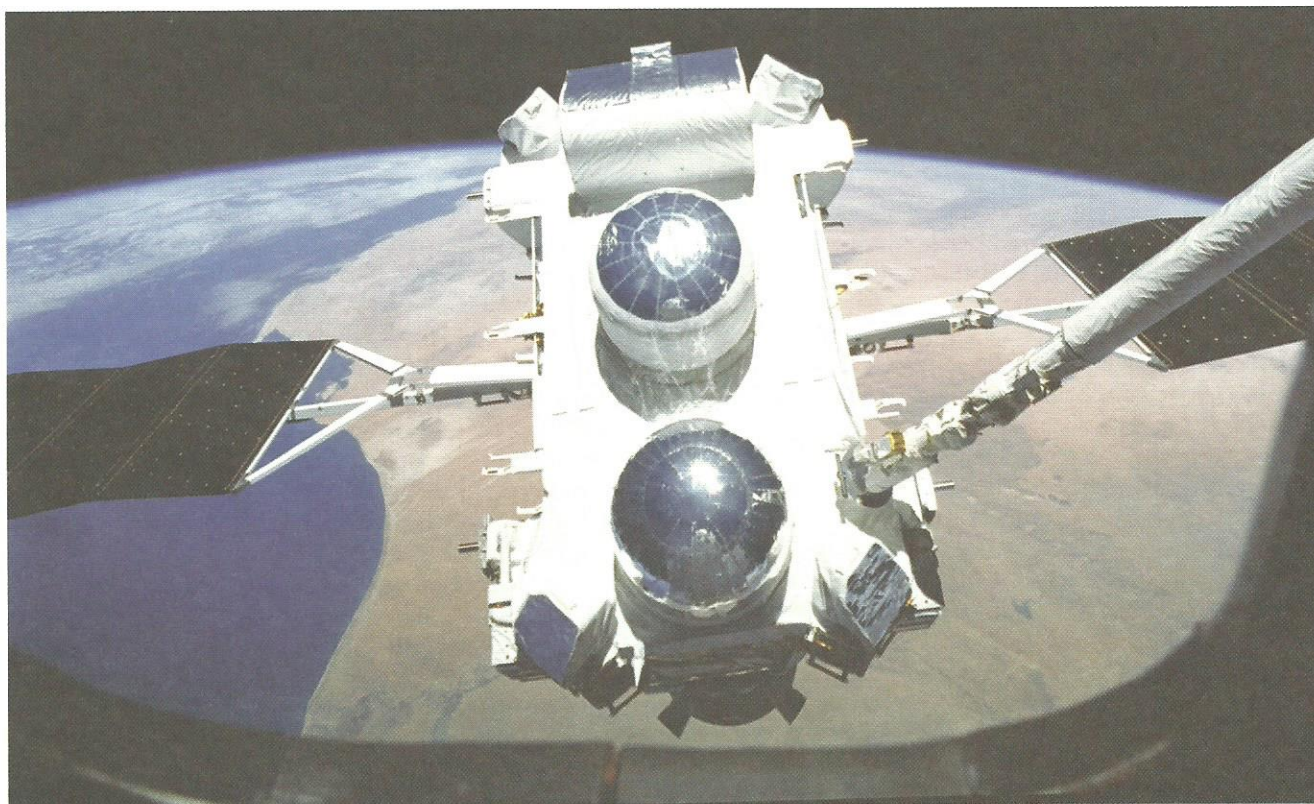
ASTROPHYSICS. Telescopes equipped with prisms that split starlight into rainbow-like spectra made possible investigations of the physical and chemical nature of astronomical objects. In 1802, the English chemist William Wollaston found several dark lines in the solar spectrum, and in 1814, the German optician Joseph Fraunhofer observed and catalogued hundreds of solar lines. In 1859, Gustav Kirchhoff, professor of physics at the University of Heidelberg, showed that each element produces its own pattern of spectral lines. In the first qualitative chemical analysis of a celestial body, Kirchhoff compared laboratory spectra from thirty elements

to the Sun's spectrum and found matches for iron, calcium, magnesium, sodium, nickel, and chromium.

The English astronomer William Huggins, tired of making drawings of planets and timing the meridian passage of stars, likened news of Kirchhoff's work to "coming upon a spring of water in a dry and thirsty land." Huggins suggested to his friend and neighbor, William Allen Miller, a professor of chemistry at Kings College, London, that they commence observations of stellar spectra. Initially Miller doubted the wisdom of applying Kirchhoff's methods to the stars, because of their faint light; but by 1870, Huggins and Miller had identified several elements in spectra of stars and nebulae.

Spectroscopic techniques were also employed to measure motion in the line of sight. In 1842, Johann Christian Doppler, an Austrian physicist, argued that motion of a source of light should shift the lines in its spectrum. A more correct explanation of the principle involved was presented by the French physicist Armand-Hippolyte-Louis Fizeau in a paper read in 1841 but not published until 1848. Not all scientists accepted the theory. In 1868, however, Huggins found what appeared to be a slight shift for a hydrogen line in the spectrum of the bright star Sirius, and by 1872, he had more conclusive evidence of the motion of Sirius and several other stars. Early in the twentieth century Vesto M. Slipher at the Lowell Observatory in Arizona measured Doppler shifts in spectra of faint spiral nebulae, whose receding motions revealed the expansion of the universe.

Instrumental limitations prevented Huggins from extending his spectroscopic investigations to other galaxies. Astronomical entrepreneurship in America's gilded age saw the construction of new and larger instruments and a shift of the center of astronomical spectroscopic research from England to the United States. Also, a scientific education became necessary for astronomers, as astrophysics predomi-



The Compton Observatory (for detecting gamma rays) at the end of the manipulator arm of Shuttle Atlantis. The observatory was launched in 1991.

nated and the concerns of professional researchers and amateurs like Huggins diverged.

George Ellery Hale, a leader in founding the *Astrophysical Journal* in 1895, the American Astronomical and Astrophysical Society in 1899, the Mount Wilson Observatory in 1904, and the International Astronomical Union in 1919, was a prototype of the high-pressure, heavy-hardware, big-spending, team-organized scientific entrepreneur. While an undergraduate at the Massachusetts Institute of Technology in 1889, he invented a device to photograph outbursts of gas at the Sun's limb. He continued studying the Sun at his home observatory and then at the Yerkes Observatory of the University of Chicago. In 1902, Andrew Carnegie established the Carnegie Institution of Washington with a \$10,000,000 endowment for research, exceeding the total of endowed funds for research of all American colleges combined. With grants from the Carnegie Institution, Hale built the Mount Wilson Observatory with a 60-inch reflecting telescope in 1908 and a 100-inch completed in 1917. In his own research, Hale in 1908 detected the magnetic splitting of spectral lines from sunspots.

Stellar spectra were obtained at the Harvard College Observatory and catalogued in a project begun in 1886 and continued well into the twentieth century. Women did much of the tedious computing work. Edward Charles Pickering, the newly appointed director of the Harvard College Observatory in 1881 and an advocate of advanced study for women, declared that even his maid could do a better job of copying and computing than his incompetent male assistant. And so she did. And so did some twenty more women over the next several decades, recruited for their steadiness, adaptability, acuteness of vision, and willingness to work for low wages. Initially the stars were catalogued alphabetically, beginning with A, on the strength of their hydrogen lines, but Annie Jump Cannon found a continuous sequence of gradual changes among them: O, B, A, F, G, K, M, R, N, S (mnemonically: Oh, be a fine girl; kiss me right now, Sweet.). Antonia Maury added a second dimension to the classification system by noting that spectral lines were narrower in more luminous, giant stars of the same spectral class. Cecilia Payne-Gaposkin, a graduate student at Harvard, determined from spectra relative abundances of elements in stellar atmospheres. Her Ph.D. thesis of 1925, published as *Stellar Atmospheres*, has been lauded as the most brilliant thesis written in astronomy. She received her degree from Radcliffe College, however—Harvard did not then grant degrees to women—and later when employed at Harvard she was initially budgeted as “equipment.”

Ejnar Hertzsprung in Copenhagen and Henry Norris Russell at Princeton University independently, in 1911 and 1913 respectively, related spectral class to luminosity. The Hertzsprung-Russell diagram was used to estimate distances by determining spectral class, reading absolute brightness off the diagram, and comparing that to the observed brightness diminished by distance. Once the source of stellar energy became better known, evolutionary tracks of stars would be drawn on the H-R diagram.

By the middle of the nineteenth century, discussions of the source of solar energy had rejected chemical combustion, which would have burnt away a mass as large as the Sun in only 8,000 years. From 1860 on, William Thomson (Lord Kelvin) switched from an influx of meteoritic matter as the Sun's energy source to gravitational contraction. Thomson estimated the age of the Sun at twenty million years, less than a tenth that required by Darwin's theory of

evolution. In 1903 Pierre and Marie Curie measured the heat given off by a gram of radium. This hitherto unknown source of energy opened up vast spans of time for geological and biological evolution, though astronomers were slow to abandon gravitational contraction.

In 1938, the German-born Hans Bethe (b. 1906), then at Cornell University, proposed a plausible mechanism for energy production in stars. He knew much about atoms but little about stellar interiors when he attended a conference in April 1938 reviewing the problem of thermonuclear sources in stars. Shortly thereafter, Bethe worked out the carbon cycle. It begins with a carbon-12 nucleus; adds four protons in stages, converting the carbon to nitrogen and then to oxygen; and ends in nuclei of carbon-12 and helium-4 plus energy. A bit later Bethe also envisioned a proton-proton reaction: two protons (hydrogen nuclei) form a nucleus of deuterium (one proton becoming one neutron); the addition of a third proton creates a helium-3 nucleus (two protons, one neutron), two of which collide to form helium-4 (two protons, two neutrons) while ejecting two protons. The net result in both cases is the fusion of four hydrogen nuclei into one helium nucleus plus a release of energy. The proton-proton reaction provides the main source of energy in stars about the mass of our Sun, 70 percent of which is hydrogen and 28 percent helium. In more massive and hotter stars with more heavy elements, the carbon cycle is more important. Bethe received the Nobel Prize in 1967 for his work on the mechanisms of energy production in stars.

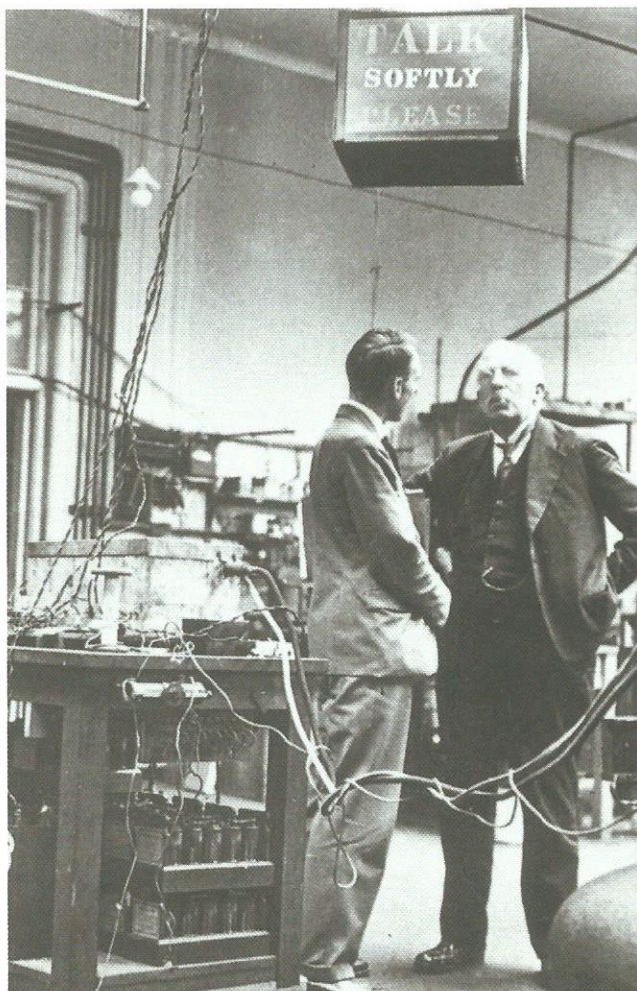
NORRIS S. HETHERINGTON

ATOMIC STRUCTURE. By 1890, much evidence had accumulated that the atom of chemistry and the molecule of physics must have parts. The chemical evidence included analogies between the behavior of dilute solutions and of gases, as developed in the ionic theory of Svante Arrhenius (Nobel Prize in chemistry, 1903), and the implication from the periodic table that the elements must have some ingredient in common. The physical evidence included the emission of characteristic spectra, which was likened to the ringing of a bell, and the formation of ions in gas discharges.

Sommerfeld's “Ellipsenverein” showing the linked motions of five electrons described similar precessing elliptical orbits; at any instant the electrons occupy the vertices of a rotating, pulsating pentagon.

Study of the rays emanating from the cathode in these discharges prompted Joseph John Thomson (Nobel Prize in physics, 1906) to assert in 1897 that the rays consisted of tiny charged corpuscles, which made up chemical atoms and constituted their common bond, and also emitted spectral lines and proffered the key to ionization. This hazardous extrapolation quickly received confirmation. Thomson showed that the ions liberated from metals by ultraviolet light had the same low mass-to-charge ratio (m/e) as corpuscles, around one one-thousandth the corresponding ratio for hydrogen atoms in electrolysis. Thomson's student Ernest Rutherford (Nobel Prize in chemistry, 1908) determined that the rays from radioactive substances consisted of two sorts, one, alpha, unbendable, the other, beta, bendable, by a magnetic field; he and the discoverer of radioactivity, Henri Becquerel (Nobel Prize in physics, 1903), showed by the degree of bending that beta rays also had a very small m/e .

Indication of the presence of corpuscles within atoms came from the magnetic splitting of spectral lines accomplished by Pieter Zeeman (Nobel Prize in physics, 1902) as elucidated by Hendrik Antoon Lorentz (Nobel Prize in



New Zealand-born physicist Ernest Rutherford (1871–1937) seen in the Cavendish Laboratory, Cambridge, England, ca. 1930, of which he was the director. He was known for his booming voice as well as for his brilliance.

physics, 1902). Lorentz traced spectra to the vibrations of “ions” whose m/e , as determined from Zeeman’s magneto-optical splitting, was very close to those of the cathode ray, photo-electric, and beta-ray particles. The omnipresent corpuscle became the electron around 1900 when experiments at Thomson’s laboratory at Cambridge indicated that the charge on corpuscles was about the same as that on a hydrogen ion.

Thomson was a leader of the British school, largely Cambridge trained, who, to paraphrase another of its lights, William Thomson, Lord Kelvin, understood a problem best after constructing a physical model of it. Thomson supposed that the corpuscle-electrons constituting an atom circulated within a spherical space that acted as if filled with a homogeneous, unresisting, diffuse, weightless positive charge. On this last assumption, an atom of mass A would contain around $1,000A$ electrons. In 1904 Thomson exhibited analogies between a swarm of electrons circulating in concentric rings and the chemical properties of the elements. He thus introduced the important idea that one element differed from another only in its electronic structure. In 1906, having calculated the capacity of his model atoms to scatter X rays and beta rays, he deduced that the number of scattering centers was more nearly $3A$ than $1000A$, thus giving weight and reality to the positive charge.

In 1910, Rutherford and Hans Geiger showed that alpha particles could be scattered through large angles. Rutherford

inferred that Thomson’s latest estimate was still too high. The scattering experiments indicated that the charges making up an individual scatterer acted as if assembled together at one point. Such an assemblage needed a smaller total charge to deflect an alpha particle through a given angle than a diffuse scatterer. Thus the atomic nucleus, which in Rutherford’s original formulation could be either positive or negative, entered physics. He soon chose a positive center carrying the entire mass A and a charge of around $Ae/2$. Rutherford’s student Henry G. J. Moseley then (in 1913–1914) deduced from his examination of characteristic X-ray spectra that the nucleus could be characterized by a whole number Z , beginning at 1 with hydrogen and increasing by a unit thereafter through the periodic table. Rutherford’s school associated Z (the “atomic number”) with the positive charge on the nucleus and recognized it to be a more reliable indicator of chemical nature than atomic weight. Classification by Z allowed an explanation of the few places in the periodic table where chemical properties did not follow weight and provided space for the accommodation of isotopes according to the ideas put forward by Rutherford’s former colleagues Frederick Soddy (Nobel Prize in chemistry, 1921), Georg von Hevesy (Nobel Prize in chemistry, 1943), Kasimir Fajans, and others around 1913.

During a study trip to Rutherford’s laboratory in 1911, Niels Bohr (Nobel Prize in physics, 1922) convinced himself that the nuclear atom was the route to a theory of atomic structure much better than Thomson’s. One cause of his conviction was that ordinary electrodynamics required that a nuclear hydrogen atom with one electron could destroy itself instantly by radiation, whereas atoms stuffed with electrons could last a very long time. By presenting the problem of the existence of atoms in its strongest form, the nuclear hydrogen atom appealed to Bohr’s dialectical mind. He solved the problem by fiat, by declaring that electrons could circulate in atoms only on orbits restricting their angular momenta to integral multiples of the quantum of action. With this condition Bohr derived the wavelengths of the spectra of hydrogen and ionized helium and gave indications of the nature of molecular bonding in (1913–1914). Arnold Sommerfeld extended the scheme to spectra containing doublets and triplets, and also to the X-ray spectra investigated by Moseley and Manne Siegbahn (Nobel Prize in physics, 1924).

Physicists returning from World War I found that Bohr (who as a Dane had been neutral), Sommerfeld (who was too old to fight), and their coworkers had made Bohr’s combination of ordinary mechanics and quantum conditions into a hybrid, inconsistent, vigorous theory where none had existed before. Reasoning about electrons orbiting nuclei in quantized orbits, they could explain many features of atomic spectra, ionization and electron impact, and molecular bonding. The high point of the hybrid approach, known subsequently as “the old quantum theory,” came in 1922, when Bohr claimed to be able to derive the lengths of the periods of the table of elements. But by then quantitative mismatches between theory and data on atoms more complicated than hydrogen had begun to undermine confidence in the internally structured mechanical atom. During the years between 1925 and to 1927, it was superseded by ascribing non-mechanical spin, unsociability (Pauli Exclusion), and exchange forces to the electron, and by replacing the Bohr-Sommerfeld equations with matrix and wave mechanics. Physicists declared that they knew everything

about the atom “in principle” and moved their model-making into the recesses of the nucleus.

J. L. HEILBRON

ATOMIC WEIGHT. In his work of the 1770s and 1780s, Antoine-Laurent Lavoisier took weight to be the central measure of amount of material; when he defined a chemical element as a chemically undecomposable substance, he took loss of weight as his criterion for decomposition. In the generation after Lavoisier’s death, chemists developed ideas about chemical atoms whose single measurable feature was their weight. Since the absolute weight of an object as small as an atom could not be measured, atomic weights have always been expressed in units relative to a conventional standard.

Determining the relative weights of the atoms of each of the elements involved three pragmatic issues: first, choosing that conventional standard; second, determining the formulas for the compounds used to derive the atomic weights; and third, achieving the greatest possible accuracy in measurement. Among the first generation of chemical atomists, John Dalton, Humphry Davy, and William Prout chose the fiducial standard that the atom of hydrogen = 1 exactly; on the other hand, Thomas Thomson chose oxygen = 1, William Wollaston chose oxygen = 10, and Jöns Jacob Berzelius chose oxygen = 100. By the middle of the nineteenth century, nearly every chemist had adopted the hydrogen standard, which is still used today in modified form (namely, carbon-12 = 12 exactly, which places hydrogen very close to 1).

Throughout the nineteenth century, the chemist had to determine (or to *assume*, if empirical determination proved impossible) the formulas for any chemical compounds used to derive atomic weights. For example, Dalton’s data (1810) indicated that water consists of 87.5 percent oxygen and 12.5 percent hydrogen. He assumed that molecules of water consist of an atom of hydrogen united to an atom of oxygen; consequently oxygen weighed 7 using the standard of hydrogen = 1. By contrast, Davy and Berzelius (in 1812 and 1814, respectively) took H_2O rather than HO as the formula for water. In this case, *two* atoms of hydrogen must make up the same quantity that one did in the previous case, so hydrogen must be 0.5 on the scale of oxygen = 7, or if $\text{H} = 1$, then $\text{O} = 14$. Actually, Berzelius’s more precise chemical analysis indicated that water consisted of 88.8 percent oxygen by weight, making the weight of an oxygen atom 16 if calculated on the scale $\text{H} = 1$.

Since no physical methods for the determination of chemical formulas existed at the beginning of the nineteenth century, the varying assumptions about formulas led to conflicting systems of atomic weight, many of which gave values for the same atom that differed by small integral multiples (such as $\text{O} = 8$ versus $\text{O} = 16$). Only gradually did chemists learn how to determine formulas in a way that could command a consensus in the specialist community. By the 1860s, most European chemists had come to agreement on a single system of atomic weights and formulas, nearly identical with that used today. Still, many fine chemists in France continued to accept HO as the formula of water, until they too converted to the majority viewpoint in the 1890s.

The dispute between Dalton and Berzelius over hydrogen, oxygen, and water also illustrates the significance of accuracy in gravimetric analyses of compounds to arrive at precise atomic weights. Since many atomic weights appeared to be

true, all atoms might be built up from subatomic particles that represented the integral weight units—perhaps hydrogen atoms themselves. “Prout’s hypothesis,” as it came to be known, was formally proposed in 1815.

Berzelius rejected the hypothesis on empirical grounds. Thomson and others, he said, were letting their predilection damage their objectivity. An extended discussion between Berzelius, Justus von Liebig, Jean-Baptiste-André Dumas, Charles Marignac, and others between 1838 and 1849 over the relative atomic weights for the crucial elements hydrogen, carbon, and oxygen established that Berzelius’s nonintegral weight for carbon was nearly 2 percent too high. The revised weights (1, 12, and 16 almost exactly) gave another boost to Prout’s hypothesis. Subsequent new determinations by the Belgian chemist J. S. Stas established that many elements had nonintegral atomic weights and drew opinion against Prout once more.

Edward Morley and T. W. Richards, who won a Nobel Prize for his work, made the finest atomic-weight determinations using purely chemical means at the end of the century. After the development of the mass spectrometer, atomic weights could be determined with great accuracy and directness. The history of the mass spectrometer is intimately connected with investigations of atomic structure, including the discovery of protons, neutrons, and isotopes. All atomic nuclei consist of integral numbers of unit masses of protons and neutrons, the elemental atomic weight being nothing more than a weighted average of all the naturally occurring isotopes of the element. There was some truth to Prout’s hypothesis after all.

A. J. ROCKE

ELEMENTS			
	Hydrogen	1	
	Strontian		46
	Azote	5	
	Barytes		68
	Carbon	5	
	Iron		50
	Oxygen	7	
	Zinc		56
	Phosphorus	9	
	Copper		56
	Sulphur	13	
	Lead		90
	Magnesia	20	
	Silver		190
	Lime	24	
	Gold		190
	Soda	28	
	Platina		190
	Potash	42	
	Mercury		167

Table of atomic weights of the “elements” together with their